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NEW TECHNIQUES OF PATTERN SHAPING FOR LOW SILHOUETTE ANTENNAS

by

A. S. THOMAS

for

Electronics Research Directorate
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

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ABSTRACT

The infinite modulated reactance sheet is studied with the phase and amplitude contours of the near field presented. It is shown that the infinite reactance sheet is an excellent description of the modulated Yagi. Experimental radiation patterns of low sidelobe endfire arrays are given together with radiation patterns of Yagi arrays giving cosecant type radiations, flat top flared beams, and beams at an arbitrary angle. The beams at an arbitrary angle are obtained from a cosine to the even power modulation of the relative wave number.

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I. INTRODUCTION

Under Contract No. AF19(604)-1714 [1,2], spatial phase modulation along a linear array was studied under the assumption of constant amplitude along the array to show the feasibility of spatial modulations. In that work no attempt was made to correlate with actual structures.

TM fields in general have been studied and then specialized to an infinite reactive surface.

W. F. Reynolds, of this firm, and independently and for different purposes, Hessel and Oliner [3,4], studied a modulated reactive sheet. The latter used the transmission line approach, while the approach at A. S. Thomas, Inc. was the field approach, both, however, as can be expected, yielding identical solutions.

It was demonstrated, as had been anticipated, that, associated with a phase modulation, there occurs an amplitude modulation and a complex relative wave number. It will be demonstrated that the impedance sheet is a good approximation to the modulated linear array. The near field was computed for the three field components and constant phase and amplitude

contours drawn.

Based on the study of phase modulation assuming constant amplitude and the study of the modulated reactance sheet, endfire arrays were designed that gave radiation patterns with 20 db sidelobes and relatively narrow beam widths in both planes. Although relatively frequency sensitive, arrays have been designed and tested giving cosecant, modified cosecant and flared flat top beams. It was demonstrated that a class of distributions of the relative wave number where the modulation is either a cosine or cosine and sine terms raised to an even power, give a beam at an arbitrary angle from endfire to beyond broadside with the position of the beam depending on the amplitude of modulation, the frequency of modulation, and the power to which the sine or cosine term is raised.

II. REACTIVE SURFACE

A. GENERAL

In order to design a phase-modulated slow wave antenna, it is desirable to know not only the spectrum of relative wave numbers that results from the spacial modulation but also the relative amplitude and phase of the fundamental and each of the side bands, together with the attenuation along the array. Since for physical structures, no exact or near exact solutions exist, an infinite reactive surface occupying the xz plane with a normalized surface reactance given by the non-negative real function

$$X(z) = j\sqrt{\frac{\epsilon}{\mu}}\ \frac{E_z}{H_x}, \tag{1}$$

and supportingTM electromagnetic fields with H_x, E_y, and E_z defined for $y \geq 0$, where ϵ and μ are the permittivity and permeability of free space, was studied to obtain insight. From the field equations, it is readily

seen that for TM waves

$$E_y = \frac{1}{j\omega\epsilon} \frac{\partial H_x}{\partial z} \tag{2}$$

$$E_z = -\frac{1}{j\omega\epsilon} \frac{\partial H_x}{\partial y} \tag{3}$$

$$H_x = -\frac{1}{j\omega\mu} \left(\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right) \tag{4}$$

$$S_x = 0, \; S_y = \tfrac{1}{2}\,\mathrm{Re}\,(E_z H_x^*), \; S_z = \tfrac{1}{2}\,\mathrm{Re}\,(-E_y H_x^*) \tag{5}$$

where S_x, S_y, and S_z are the time-averages of the energy flux.

Now let

$$H_x = |H_x| \; e^{j\Psi(y,z)} \tag{6}$$

where $\Psi(y,z)$ is real and represents the phase of H_x in radians. It is convenient to consider the logarithm of H_x and differentiate with respect to y and z giving

$$\frac{\partial(\ln H_x)}{\partial z} = \frac{\partial(\ln|H_x|)}{\partial z} + j\,\frac{\partial \Psi}{\partial z} = \frac{\partial H_x}{H_x\,\partial z} = j\omega\epsilon\,\frac{E_y}{H_x} \tag{7}$$

$$\frac{\partial(\ln H_x)}{\partial y} = \frac{\partial(\ln|H|_x)}{\partial y} + j\,\frac{\partial\Psi}{\partial y} = \frac{\partial H_x}{H_x\,\partial y} = -\,j\,\omega\epsilon\,\frac{E_z}{H_x} \tag{8}$$

Equating real and imaginary parts of equations (8) and (9) we have

$$\frac{\partial(\ln|H|_x)}{\partial z} = \omega\epsilon\ \mathrm{Im}\,\frac{E_y}{H_x} \tag{9}$$

$$\frac{\partial\Psi}{\partial z} = -\,\omega\epsilon\ \mathrm{Re}\,\frac{E_y}{H_x} = -\,\omega\epsilon\,\frac{S_z}{|H|_x^{\,2}} \tag{10}$$

$$\frac{\partial(\ln|H|_x)}{\partial y} = \omega\epsilon\ \mathrm{Im}\,\frac{E_z}{H_x} \tag{11}$$

$$\frac{\partial\Psi}{\partial y} = \omega\epsilon\ \mathrm{Re}\,\frac{E_z}{H_x} = \omega\epsilon\,\frac{S_y}{|H|_x^{\,2}} \tag{12}$$

Since by definition of the reactive surface $\frac{E_z}{H_x}$ is pure imaginary, then $\frac{\partial\Psi}{\partial y} = 0$ and $S_y = 0$. Hence, the lines of constant phase are normal to the reactive surface and there is no energy flow on the time average through an

infinite reactive plane in either direction. From equation (10), it is seen that

$$|H|_x = \sqrt{\omega\epsilon}\sqrt{\frac{S_z}{-\partial\Psi/\partial z}} . \qquad (13)$$

On the surface y = 0,

$$\frac{1}{2\pi}\,\frac{\partial\Psi}{\partial z} = \delta(z). \qquad (14)$$

This is the instantaneous relative wave number $\delta = \beta/k$ where β is the wave number along the surface and k is the free space wave number.

Again consider the following solutions of the field equations:

$$H_x = e^{-\alpha y - j\beta z} \qquad (15)$$

$$E_y = \frac{-\beta}{\omega\epsilon}\, e^{-\alpha y - j\beta z} \qquad (16)$$

$$E_z = \frac{-j\alpha}{\omega\epsilon}\, e^{-\alpha y - j\beta z} \qquad (17)$$

where

$$\beta^2 = \alpha^2 + k^2$$

$$k^2 = \omega^2 \mu\epsilon$$

$$\omega = 2\pi f$$

f = the frequency

From (17) and (18), it is readily seen that a reactive surface along the xy plane can support the field since

$$X(z) = j\sqrt{\frac{\epsilon}{\mu}} \; \frac{E_z}{H_x} = \frac{\alpha}{k} \tag{18}$$

hence

$$\delta = \frac{\beta}{k} = \pm\sqrt{X^2(z) + 1} = \frac{1}{2\pi} \; \frac{d\Psi}{dz} \tag{19}$$

Placing this result in (13), we have

$$\left|H_x\right| = \omega\epsilon\sqrt{\frac{S_z}{\sqrt{X^2(z) + 1}}} . \tag{20}$$

This result should be compared with the following expression suggested by F. H. Zucker

$$H_x = C \sqrt{\frac{X(z)}{\sqrt{X^2(z)+1}}}\; e^{-k\int \sqrt{X^2(z)+1}\, dz} \tag{21}$$

which would represent an excellent approximation if S_z were proportional to $X(z)$, however this would mean no energy flow for $X(z) = 0$. Nevertheless, other than the fact that this gives for the modulated impedance sheet a real δ with no attenuation in the z direction, it will be shown that the numerical results agree quite closely with those obtained from the exact formulation for real amplitude and δ.

It is of interest to consider for TM waves, the case of constant amplitude and modulated phase $\Psi(0, z)$ such that

$$H_x = C\, e^{-j\Psi(0, z)}, \tag{22}$$

then from (2) and (3)

$$E_y = -\frac{C}{\omega\epsilon}\,\frac{\partial\Psi(0, z)}{\partial z}\, e^{-j\Psi(0, z)} = -\frac{1}{f\epsilon}\,\delta(z) H_x \tag{23}$$

and

$$E_z = 0 . \tag{24}$$

This result implies that for phase modulated surface wave structures such as Yagis, discs on rod, etc., there will be an inherent amplitude modulation.

B. RIGOROUS SOLUTION OF MODULATED REACTANCE SHEET

Let $X(z)$ be periodic such that

$$X(z+a) = X(z) \tag{25}$$

and that the field satisfies the Floquet condition

$$H_x(y, z) = e^{-jk\delta_o z}\hat{H}_x(y, z) \tag{26}$$

where

δ_o is a complex constant, and

$$\hat{H}_x(y, z+a) \equiv \hat{H}_x(y, z). \tag{27}$$

This implies the corresponding relations for E_y and E_z.

The Fourier theorem shows that we have an expansions of the form

$$H_x(y, z) = \sum_{n=-\infty}^{\infty} (A_n e^{-k\gamma_n y} + B_n e^{k\gamma_n y}) e^{-jk\delta_n z} \tag{28}$$

where

$$\delta_n = \delta_o + n\, p,$$

$$p = \frac{\lambda}{a}, \text{ and}$$

$$\gamma_n^2 = \delta_n^2 - 1;$$

the presence of both A_n and B_n terms is due to the existence of two complex square roots of $\delta_n^2 - 1$.

If this is restricted, for physical reasons, to fields whose components are surface waves attenuated as they travel in either z direction, and radiated waves traveling outward from the surface and possibly attenuating as z increases, the B_n term in (28) can be omitted and the square

roots of $\delta_n^2 - 1$ chosen so that

$$\mathrm{Im}\gamma_n \leq 0 \text{ for } \mathrm{Re}\delta_n < 1, \text{ and} \tag{29}$$

$$\mathrm{Im}\gamma_n \geq 0 \text{ for } \mathrm{Re}\delta_n > 1 \tag{30}$$

then H_x, E_y, and E_z are as follows

$$H_x = \sum A_n e^{-k\gamma_n y - jk\delta_n z} \tag{31}$$

$$E_y = -\frac{k}{\omega\epsilon} \sum \delta_n A_n e^{-k\gamma_n y - jk\delta_n z} \tag{32}$$

$$E_z = -\frac{jk}{\omega\epsilon} \sum \gamma_n A_n e^{-k\gamma_n y - jk\delta_n z} \tag{33}$$

giving the following expressions for X(z):

$$X(z) = \frac{\sum \gamma_n A_n e^{-jnpz}}{\sum A_n e^{-jnpz}} \tag{34}$$

the periodic function X(z) has a complex Fourier series:

$$X(z) = \sum C_n e^{-jnpz} \tag{35}$$

From (34) and (35) by substituting, multiplying, and equating coefficients, the following expression is

obtained:

$$\gamma_n A_n = \sum_{n_1+n_2=n} C_{n_1} A_{n_2}. \tag{36}$$

Now let

$$X(z) = X_o(1+M\cos kpz),$$

$$X_o > 0, \tag{37}$$

$$M \leq 1$$

and write equation (35) as follows:

$$X(z) = X_o(1+\frac{M}{2}(e^{jkpz}+e^{-jkpz})) = \sum C_n e^{-jnkpz} \tag{38}$$

giving

$$C_o = X_o,\ C_1 = \frac{M}{2},\ \text{and } C_{-1} = \frac{M}{2}. \tag{39}$$

which when substituted in equation (37) gives the basic difference equation

$$\gamma_n A_n = \frac{M}{2} X_o A_{n-1} + X_o A_n + \frac{M}{2} X_o A_{n+1} \tag{40}$$

which may be written as follows:

$$A_{n-1} + W_n A_n + A_{n+1} = 0 \tag{41}$$

where

$$W_n = \frac{2}{M}\left(1 - \frac{\gamma n}{X_o}\right).$$

This is identical to the result obtained by Oliner and Hessel by an alternate method. The coefficients of the difference equation (41), given X_o, M, and p, depend on the constant δ_o. The basic condition on δ_o is that (41) should have a non-zero solution for which $\sum_{n=-\infty}^{\infty} |A_n|^2$ is finite. It can be demonstrated that for

$$\left(W_1 - \cfrac{1}{W_2 - \cfrac{1}{W_3 - \cdots}}\right)\left(W_o - \cfrac{1}{W_{-1} - \cfrac{1}{W_{-2} - \cdots}}\right) = 1 \tag{42}$$

(41) has the continued fraction solutions

$$\frac{A_n}{A_{n+1}} = - \cfrac{1}{W_n - \cfrac{1}{W_{n-1} - \cfrac{1}{W_{n-2} - \cdots}}} \quad \text{for } n = -1, -2, -3 \ldots \tag{43}$$

$$\frac{A_n}{A_{n+1}} = - \cfrac{1}{W_{n+1} - \cfrac{1}{W_{n+2} - \cfrac{1}{W_{n+3} - \cdots}}} \text{ for } n=0,\ 1,\ 2\ldots \tag{44}$$

C. COMPUTATION OF THE NEAR FIELD

The phase and amplitude of the near field for H_x, E_y, and E_z may be obtained from equations (31), (32), and (33) provided δ_o and A_n are known. The coefficients A_n may be readily obtained from (43) and (44) if the relationship (42) is satisfied. Hence the first step is to obtain the required δ_o.

1. Computation of δ_o

The "zero-th" order approximation of δ_o is given by

$$\delta_o^{(o)} = \sqrt{X_o^{\,2} + 1} \tag{45}$$

and the first order approximation is given by

$$\delta_o^{(1)} = \delta_o^{(o)} - \frac{X_o^{\,2} M^2}{4\delta_o^{(o)}} \left(\frac{1}{1 - \frac{\gamma_{-1}^{(o)}}{X_o}} + \frac{1}{1 - \frac{\gamma_1^{(o)}}{X_o}} \right) \tag{46}$$

the accuracy of the approximation may be determined from the ratio

$$\phi^{(m)} = \frac{D_+^{(m)}}{D_-^{(m)}} \qquad (47)$$

where $$D_+^{(m)} = W_1^{(m)} - \cfrac{1}{W_2^{(m)} - \cfrac{1}{W_3^{(m)} - \cdots}}$$

$$D_-^{(m)} = \cfrac{1}{W_o^{(m)} - \cfrac{1}{W_{-1}^{(m)} - \cfrac{1}{W_{-2}^{(m)} - \cdots}}}$$

m is the order of the approximation.

If, $\phi^{(m)} = 1.0$, the value of $\delta^{(m)}$ obtained is exact, hence the closeness of $\phi^{(m)}$ to 1.00 determines the accuracy of the approximation. If neither $\delta_o^{(0)}$ or $\delta_o^{(1)}$ are sufficiently close approximations, then higher order approximations may be obtained from the following relationship:

$$\delta_o^{(m)} = \delta_o^{(m-1)} + \frac{(1-\phi^{(m-1)})(\delta_o^{(m-2)} - \delta_o^{(m-1)})}{\phi^{(m-2)} - \phi^{(m-1)}} \qquad (48)$$

2. Computed Fields

Assuming X(z) as follows:

$$X(z) = \left(1+0.4\cos \frac{\pi}{\lambda_o} z\right) \tag{49}$$

the spectrum, amplitude, phase, and Poynting vector were computed. However, before the detailed computations from the rigorous solution are presented, it is interesting to compare the results from the approximation given in equation (21) with the rigorous solution. Table I compares the spectrum obtained from the approximation with that from the exact method which shows attenuation (complex δ_n's). The A_n's are the amplitude and phase of the δ_n's. Here the A_n's from the exact method are, with the exception of A_o, complex while those from the approximation are all real. The agreement is best for the slow wave side bands (negative n). The relative amplitude for H_x from the exact solution and the approximation is given in Figure 1. The relative wave number $\delta(z)$ from the approximation and the exact method seem to agree quite well in this case as is seen by Figure 2 with the major difference being at the extremes of the excursions in $\delta(z)$.

	EXACT METHOD		APPROXIMATION	
n	δ_n	A_n	δ_n	A_n
3	-0.0650 - j0.0086	0.0013 - j0.0037	-0.0858	0.0026
2	0.4350 - j0.0086	0.0123 + j0.0249	0.4142	0.0089
1	0.9350 - j0.0086	-0.1751 - j0.0657	0.9142	-0.2384
0	1.4350 - j0.0086	1.0000	1.4142	1.0000
-1	1.9350 - j0.0086	0.3209 + j0.0051	1.9142	0.3480
-2	2.4350 - j0.0086	0.0536 + j0.0013	2.4142	0.0551
-3	2.9350 - j0.0086	0.0062 + j0.0002	2.9142	0.0061

TABLE 1. Comparison of spectrum by approximation and exact method for $X_o = 1$, $M = 0.4$ and $a = 2\lambda_o$.

The amplitude and phase of H_x computed by the exact method are given in Figures 3 and 4. These illustrate that the lines of constant phase are normal to the surface as is readily seen from equation (12) where $\frac{\partial \Psi}{\partial y} = 0$ for $y=0$ and $\frac{E_z}{H_x}$ is pure imaginary.

Since $H_x(y, z/\lambda_o+2) = e^{-j\beta(2\lambda_o)} H_x(y, z/\lambda_o)$, where β is a complex constant and the field is not periodic in z/λ_o, a shift from z/λ_o to $z/\lambda_o + 2$ gives a phase shift of 5.740π and a decrease in the amplitude due to attenuation by a factor of 0.897. In Figure 3 the amplitude contours, drawn in broken line, illustrate this effect. For example, the contour 0.25, when translated $2\lambda_o$ to the right, retains its shape but becomes the contour 0.224. Again, the contour 0.20, when translated $2\lambda_o$ to the right, retains its exact shape but becomes the contour 0.174.

The constant phase contours of Figure 4 were calculated for phase differences of $\pi/4$. Since in every $2\lambda_o$ there is a phase difference of 5.740π, the contour $3\pi/2$ at the left, which starts at $y/\lambda_o=0$ and $z/\lambda_o = -1.938$, repeats as the contour 1.74π at $y/\lambda_o=0$ and $z/\lambda_o=0.062$. However, in Figure 4

the contour $7\pi/4$ is drawn which leads this contour by 0.01π and is $0.0035\lambda_o$ to the right. In the neighborhood of the intersection of a set of phase contours, there is a circling of very low level power and a null in the amplitude of H_x which occurs every $2\lambda_o$.

The constant phase and amplitude contours for E_y and E_z are given in Figures 5, 6, 7, and 8. These are similar in form to the corresponding contours for H_x. Note, in Figures 3 through 8, the direction of radiation is orthogonal to the constant phase contours with the direction of maximum radiation in the neighborhood of 25^o.

The relative wave numbers $\delta_{H_x}(z)$, $\delta_{E_y}(z)$, and $\delta_{E_z}(z)$ (the relative wave numbers associated with the three phase components) for y=0 are such that

$$\delta_{H_x}(z) = \delta_{E_z}(z) \neq \delta_{E_y}(z).$$

Although this is not readily discernible from Figures 4, 6, and 8, these are apparent in the plots of δ versus z given in Figure 9, the major difference being at the extremes of

the excursion in δ. The normalized amplitudes of H_x, E_y, and E_z are not equal as is readily seen from Figure 10.

These plots clearly show that care must be exercised in measuring the amplitude of the field since if a probe is at a given distance from a modulated array, the measured amplitude will differ significantly from that along the array. This is seen from the sketch (Figure 11) of the amplitude of E_y for the modulated reactive surface showing that the positions of the maxima and minima shift with distance from the array. If the probe were at $y=0$, the maxima of the amplitude would coincide with the maxima of δ and the minima with the minima of δ. However, as the probe is moved away from the array, the relative excursion in amplitude decreases with the maxima and minima shifting until at a distance of approximately 0.12λ from the array, the amplitude becomes constant and with increased distance, the amplitude modulation reappears, however, with the maxima of the amplitude occuring where the minima of δ occur.

Figures 12 and 13 give the calculated plots of the amplitude and orientation of the Poynting Vector. At the

surface the orientation is parallel, and in the direction of the positive Z-axis. The neighborhood of the point $y=0.33\lambda_o$ and $z=0.10\lambda_o$ is interesting in that there is a whirlpool of very low level energy with the Poynting Vector circling about this point. This repeats periodically every $2\lambda_o$. Slightly above this point, $y=0.45\lambda_o$, all of the energy is flowing out at an oblique angle from the surface. However, below $y=0.45\lambda_o$ and to the left of this whirlpool, the flow is toward the surface and to the right of this point away from the surface.

D. EXPERIMENTAL VERIFICATION

In order to determine how closely the postulated modulated reactance sheet approximates an actual physical structure, a 9λ modulated Yagi type structure was designed and tested. The Yagi elements consisted of solid alumnium rods 0.1875 inches in diameter, equally spaced 0.836 inches apart, and supported in a styrofoam column with a dielectric constant of 1.05. The modulation was obtained by means of varying the element length. The δ, as a function of element length, diameter, and spacing was based on the published results of Ehrenspeck and Poehler [5] and also those of Senacchioli and Levis [6].

1. Feed

Since a high efficiency of excitation is necessary in order to obtain reasonable agreement between the theoretical and experimental results, a highly efficient feed was developed experimentally. The feed geometry is essentially a dipole with flared arms bent so that

if they were extended, they would form a 45° - Vee. This Rabbit Ear Feed, Figure 14, is broadband with an essentially omnidirectional radiation pattern with a 2db ripple. The configuration is an outgrowth of experimenting with the relatively long wire Vee originally used by Reynolds [7]. The Rabbit Ears are fed by two equal lengths coaxial lines from the colinear arms of an E-plane tee; hence, giving a very broadband feed. For a design frequency of 2850 mcs, the feed is placed at a distance of between 1/18 and 1/16 inch from the first element of the array, with the relative wave number of the array tapered from $1.5 \leq \delta \leq 2$ over a distance greater than one-half wave length. This feed was found to give an efficiency of excitation greater than 95%. If no reflector is used with the feed, the efficiency of excitation is evidenced from the level of energy radiated in the rear quadrant.

2. Relative Wave Number and Amplitude

Having devised a high efficiency feed to minimize the perturbation of the near field by the feed radiation, the near field was studied at various distances from the modulated Yagi. It was found that the modulated Yagi is described for the field components E_y and H_x by the modulated reactance sheet. The agreement between the theoretical and experimental is evidence by the plots of $\delta(z)$ and $|E_y|$ taken at $y=0.2\lambda$ given in Figures 15 and 16. The superimposed oscillations in the amplitude are due to the elements.

3. Radiation Pattern

The radiation pattern computed on the basis of the approximation (21) is compared with the experimental radiation pattern of the modulated Yagi in Figure 17. Since equation (21) gives all real δ_n's and A_n's, the rigorous

solution of the reactance sheet as per Table 1 shows that the δ_n's are complex and, with the exception of A_o, the A_n's are complex. It is readily seen that if the attenuation were taken into account that the minima in the radiation pattern would be shallower.

E. INDEPENDENT PHASE AND AMPLITUDE CONTROL

Since independent phase and amplitude control would provide the designer with a powerful means of controlling the radiation pattern, it was decided, in spite of the result given by equations (22) and (23), namely, that an amplitude modulation is inherent to modulated surface wave structures, to study a coplanar system of Yagis. The system may be described as follows: In the XYZ coordinate system, let the central Yagi be along the Z-axis with the elements in the YZ-plane. Then each of the other parallel Yagis will be displaced equal distances to either side of the XZ-plane. The central Yagi only is fed and the side Yagis are parasitic. The hope here was that since the maxima and minima of the amplitude shift at a distance greater than 0.12λ from the driven array with the maxima of the amplitude occuring where the minimum δ of the side array occurs, that this system of modulated coplanar

Yagis could conceivably result in constant amplitude. Unfortunately, this did not happen and the amplitude modulations were but slightly altered.

III. EXPERIMENTAL RESULTS

Although the modulated reactance sheet is an excellent description of a modulated Yagi, unfortunately the rigorous formulation can take into account only one term in the modulation, whereas radiation patterns of interest require considerably more complicated modulations. Since the mathematics seemed prohibitive for more complex modulations, an experimental approach based on the results of the previous work was undertaken to obtain low-side lobe endfire arrays, shaped beams, and beams at arbitrary angles.

A. ENDFIRE

The idealized case of phase modulation with constant amplitude gave optimum theoretical end-fire radiation patterns for distributions of relative wave number, δ, having maxima at the input, center and end of the array. An example of this is given in Figure 18. This distribution for constant amplitude may be expected to give a radiation pattern with less

than 20db sidelobes and half-power angle of 23 degrees for an 8λ array. The high δ at the input is advantageous for the launching of the surface wave since it has been found that a relatively large δ is required in order to achieve a high efficiency of excitation. However, a large δ at the end of the array is not desirable, in that it would introduce a mismatch and produce a standing wave along the structure due to the reflected wave from the end. Recognizing that the amplitude modulation produced by the phase modulation results in a degradation of the radiation pattern, a careful experimental study of the radiation pattern from 3.0 to 2.6 kmcs was undertaken. The array designed according to the solid line of Figure 18 exhibited 10db first sidelobes and a beamwidth of 17 degrees. Here the beamwidth was improved; however, the sidelobes were raised considerably. The effect of the mismatch to free space was evidenced by a beam in the backward direction whose amplitude varied with frequency due to interference with the feed radiation in that direction. The addition of a taper at

the end of the array eliminated the backward beam; however, with additional degradation of the radiation pattern. It became clear from this that the phase modulated arrays with large δ at the end required modification. The buildup at the end was arbitrarily eliminated as shown by the broken line of Figure 18. This modification gave the radiation patterns of Figures 19 to 26 with the results tabulated below:

Frequency in kmcs	H.P. Angle in degrees	First Sidelobe in db down
3.00	22.0	12.0
2.95	22.0	13.0
2.90	22.5	14.0
2.85	22.5	14.5
2.80	22.0	16.0
2.75	22.5	15.5
2.70	23.0	16.0
2.65	24.5	17.0

These results warranted additional experimental

work, especially in connection with varying the excursions in δ at the center and near the ends.

A serious experimental effort led to the array design given in Figure 27, showing an initial taper in δ from 1.7 to 1.03 at the center of the array and continuing with constant δ of 1.03 to the end of the array. This array gives the radiation patterns of Figures 28 to 45, for both horizontal and vertical polarizations, with sidelobe levels 20 db down and half power angles of 20° at the design frequency. This design is not considered optimum, but merely one that gives a low sidelobe end-fire array.

B. <u>COSECANT TYPE</u>

Designing according to Figure 46, giving δ vs element length in inches, for element spacing of 0.49 inches center to center, the distribution of δ vs distance along the array of Figure 47 gave the $\csc^2\theta$ type pattern from 16° to 56° given in

Figure 48 at 2770 mcs, whereas the δ vs distance along the array given in Figure 49 gave a radiation pattern, Figure 50, that followed $\csc^2\theta \sqrt{\cot\theta}$ from approximately 16° to 60°. In essence, this requires a δ that is approximately 1.8 at the input, dropping to approximately 1.0, rising to a maximum of 1.92 at center and dropping again to 1.0 at the end of the array. Although these arrays are frequency sensitive, they nevertheless demonstrate that shaped beams may be obtained by varying the relative wave number along slow wave structures.

The distributions for the endfire case and shaped beam case differ from those computed on the basis of constant amplitude in that they are not symmetric or nearly symmetric about the center of the array. Nevertheless, the distributions obtained on the basis of constant amplitude did provide a first coarse approximation to those that gave the more satisfactory radiation patterns when the array was tapered at the end and the second order oscillations were suppressed.

C. BEAM AT ARBITRARY ANGLE

The following four parameter distribution of the relative wave number was studied in order to obtain beams at an arbitrary angle:

$$\delta = 1.0 + m_1 \cos^{2n} 2\pi pz + m_2 \sin^{2n} 2\pi pz \tag{50}$$

where	n	a positive integer
	m_1, m_2	arbitrary constants
	p	frequency of modulation
	z	distance along the array from the input in wave-length.

It has been found for $m_2 = 0.0$ and varying m_1, that for increasing m_1, the beam is moved towards endfire; while for constant m_1 increasing n, the beam is moved away from endfire towards broadside and increasing p the beam is moved in the direction of broadside. In effect, increasing m_1, is increasing δ_o and keeping the frequency of modulation constant, while increasing n is in effect an increasing of the

frequency of modulation causing the beam to swing away from endfire toward broadside, and of course, increasing p swings the beam in the direction of broadside. However, in every case, it has been found that the beam moves with increasing frequency of operation in the direction of endfire. With increased frequency of operation, there is an effective increase of m and a decrease in p, which, of course, will tend to shift the beams in the direction of endfire.

The second term in equation (50) helps in reducing the sidelobes. A 10λ array designed according to the distribution

$$\delta = 1+0.7\cos^4 0.9\pi z + 0.1\sin^4 0.9\pi z \tag{51}$$

plotted in Figure 51 gives the radiation patterns given in Figures 52 to 54. At the higher frequency the radiation pattern is endfire and as the frequency is decreased, the beam broadens forming a square

beam, Figure 53 and finally splitting giving a well defined beam, Figure 54, with a maximum at 24° and 19 db first sidelobe. An array, therefore, designed according to Figure 51 based on the δ vs length of element of Figure 46 gives an endfire radiation pattern at 3000 mcs, a square beam at 2950 mcs and a beam at 24° at 2925 mcs. Now if the number of oscillations is increased, the main beam can be made to occur at any desired angle. For example, an array designed with

$$\delta = 1+0.54 \cos^8 2.5\pi z \tag{52}$$

as given in Figure 55 has radiation patterns as given in Figures 56 to 61 with the main lobe occuring at 86° at 3200 mcs and shifting progressively with frequency to 102° at 2950 mcs. This array seems to support a relative wave number changing from $\delta=1.0$ to $\delta=1.54$ in three tenths of a free space wave length.

IV. CONCLUSIONS

Endfire slow wave Yagi type antennas with beamwidth approximately $56\sqrt{\frac{\lambda}{L}}$ and sidelobes 20 db down have been designed. These require a taper from $\delta = 1.7$ at the input to approximately $1 + \dfrac{1}{4\frac{L}{\lambda}}$ at the center, then either remaining constant to the end of the array or with but a slight taper to $\delta = 1$ at the end of the array. These antennas are relatively broadband.

Distributions of δ have been found that give, although frequency sensitive,

1.) Cosecant squared beams from 16° to 56°.

2.) Modified cosecant beams from 16° to 60°.

3.) Flared flat top beams suitable, if arrayed, for antennas with flared beam in one plane and a sharp beam in the orthogonal plane, or as feeds to parabolic reflectors. By decreasing

or increasing the length of the array and appropriately changing the distribution of the relative wave number, the beam width of the flat top beam may be altered.

4.) Beam at arbitrary angle. It has been demonstrated that distributions of

$$\delta = 1.0 + m \cos^{2n} 2\pi p z$$

can give beams at any desired angle from endfire to well beyond broadside. These exhibit a limited frequency scan. The beam near endfire, at approximately 24°, has sidelobes of approximately 20 db, while those near broadside have sidelobes of approximately 10 db. It is expected that by modifying the modulation, the sidelobe level can be improved.

Considerable insight has been obtained from the study of the modulated reactive sheet. It has been found to give an excellent description of the finite Yagi. Unfortunately, the rigorous

formulation seems to be mathematically prohibitive for the modulations necessary to produce desirable radiation patterns. Hence additional theoretical and experimental work is needed to obtain a mathematical model that will permit resynthesis. A first approximation in this direction is that of equation (21).

LIST OF REFERENCES

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2) Thomas, A. S. and F. J. Zucker, "Radiation from Modulated Surface Wave Structures - I", 1957 IRE National Convention Record, Pt. 1, pp. 153-160.

3) Hessel, Alexander, "Guiding and Scattering by Sinusoidally-Modulated Reactance Surfaces", for Air Force Cambridge Research Laboratories, Contract No. AF19(604)-2031, Research Report PIBMRI-825-60, June, 1960.

4) Oliner, A. A. and A. Hessel, "Guided Waves on Sinusoidally-Modulated Reactance Surfaces", Transactions of the IRE, Vol. AP-7, 1959, pp. S201-S208.

5) Ehrenspeck H. W. and H. Poehler, "A New Method for Obtaining Maximum Gain from Yagi Antennas", Transactions of the IRE, Vol. AP-7, No. 4, October 1959, pp. 379-386.

6) Serracchioli, F. and C. A. Levis, "The Calculated Phase Velocity of Long Endfire Uniform Dipole Arrays", Transactions of the IRE, Vol. AP-7, December 1959, pp. S424-S434.

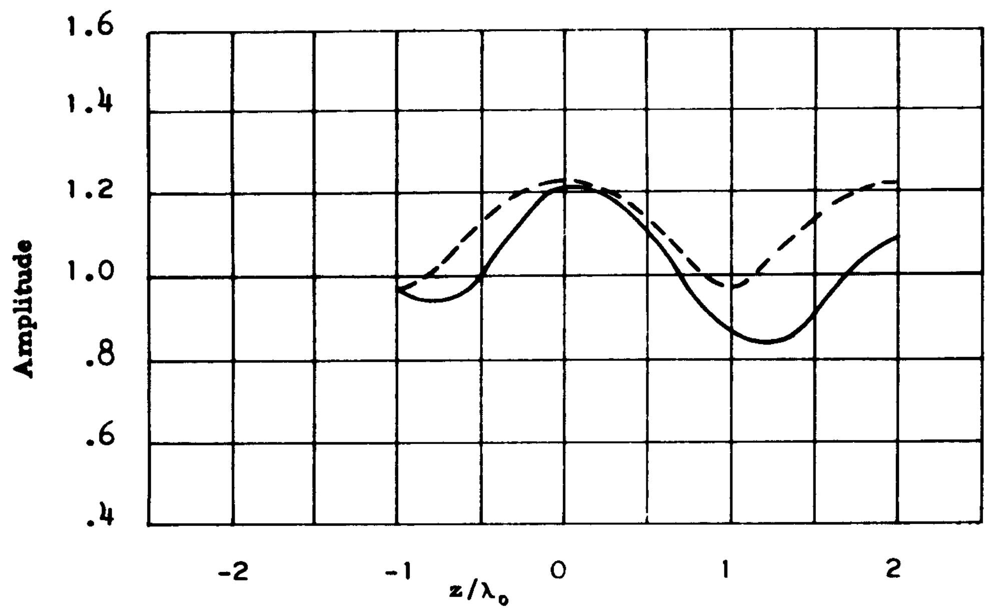

FIGURE 1. Relative Amplitude.

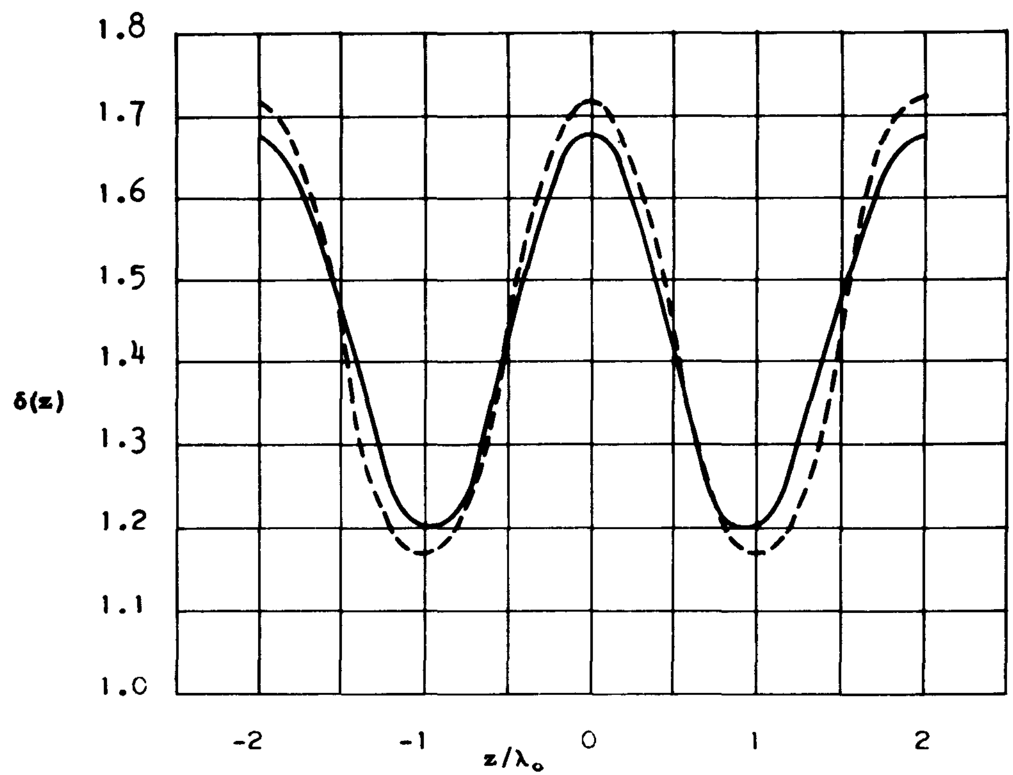

FIGURE 2. $\delta(z)$ - Relative Wave Number. ——— $\delta(z)$ for H_x

-------- Approx.

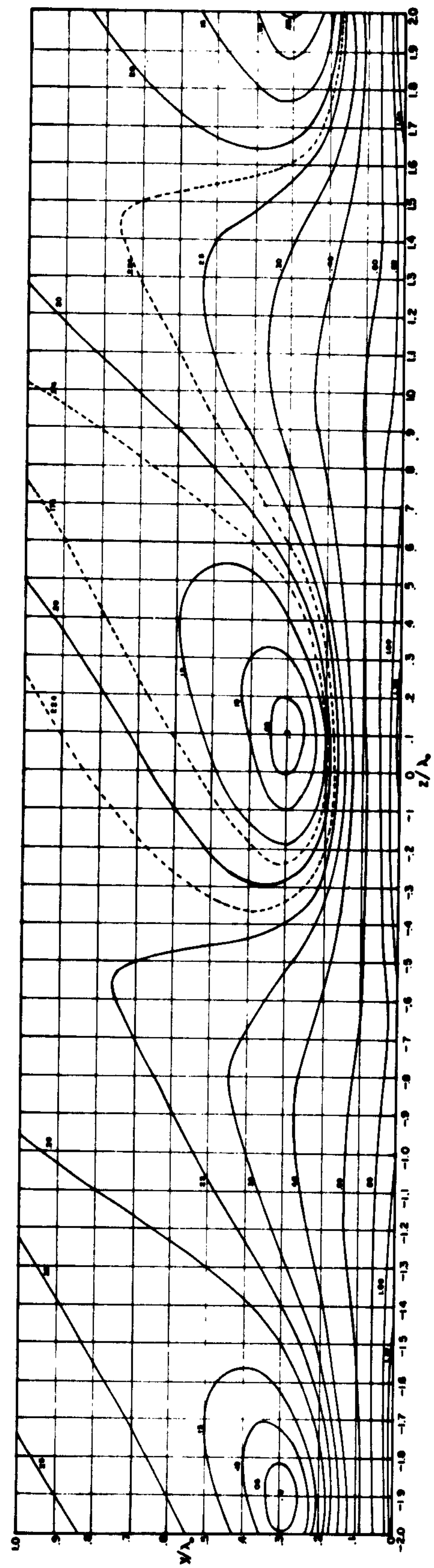

FIGURE 3 — $|E_z|$ in Near Field.

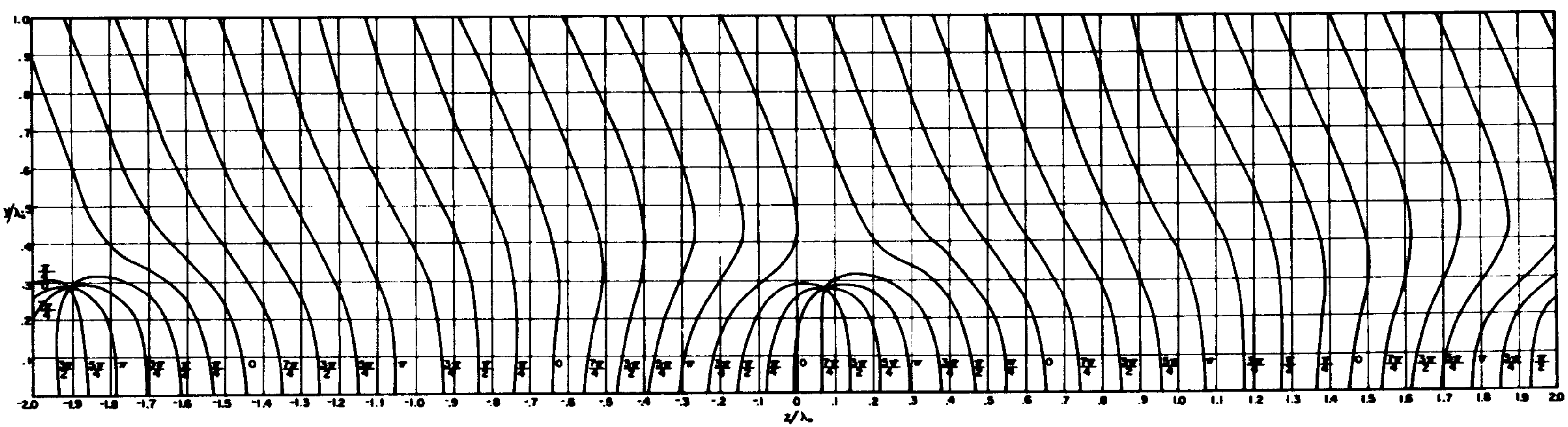

FIGURE 4 —Phase of H_z in Near Field.

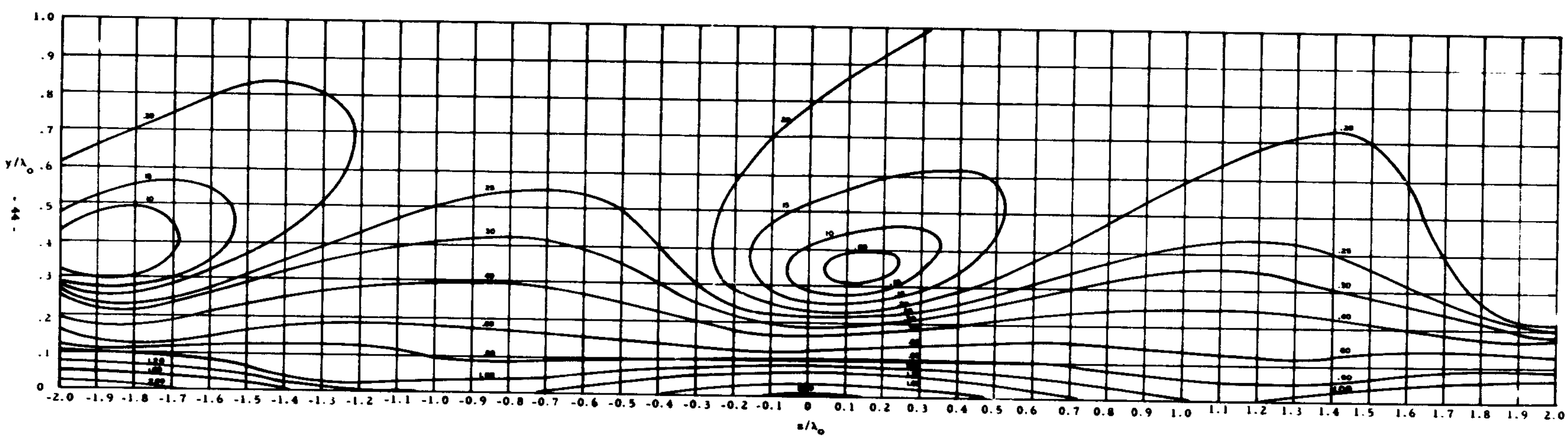

FIGURE 5. Amplitude of E_y in Near Field

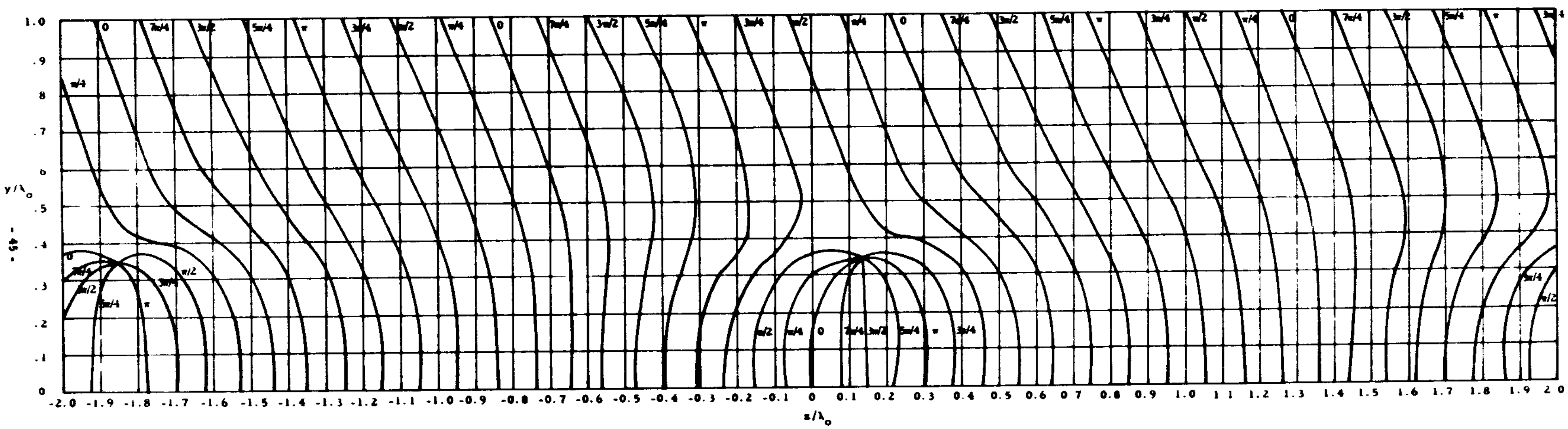

FIGURE 6. Phase of E_y in Near Field

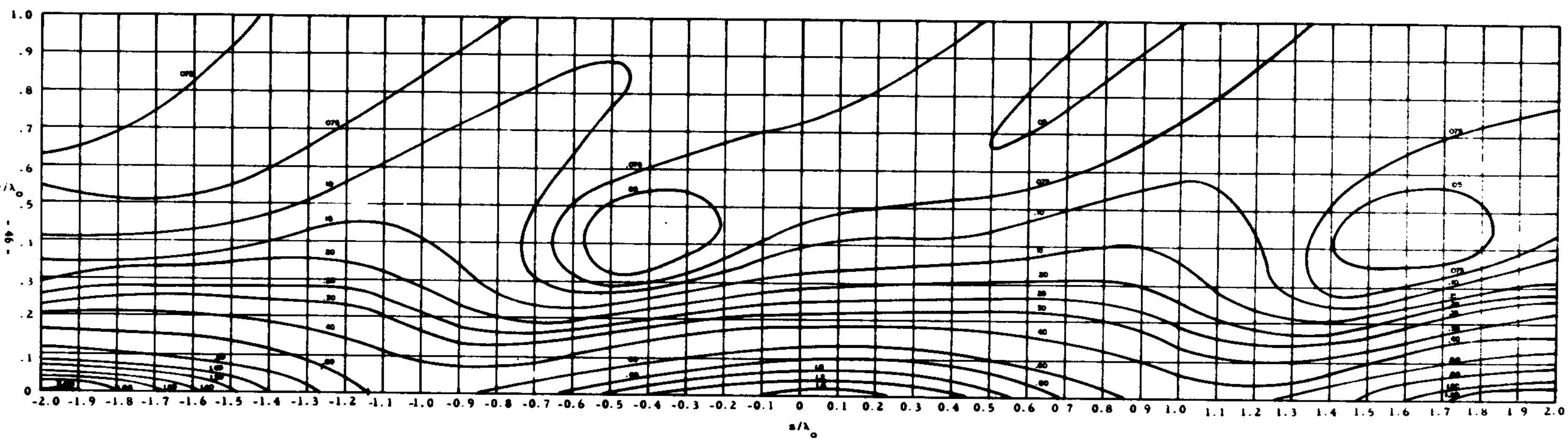

FIGURE 7. Amplitude of E_z in the Near Field

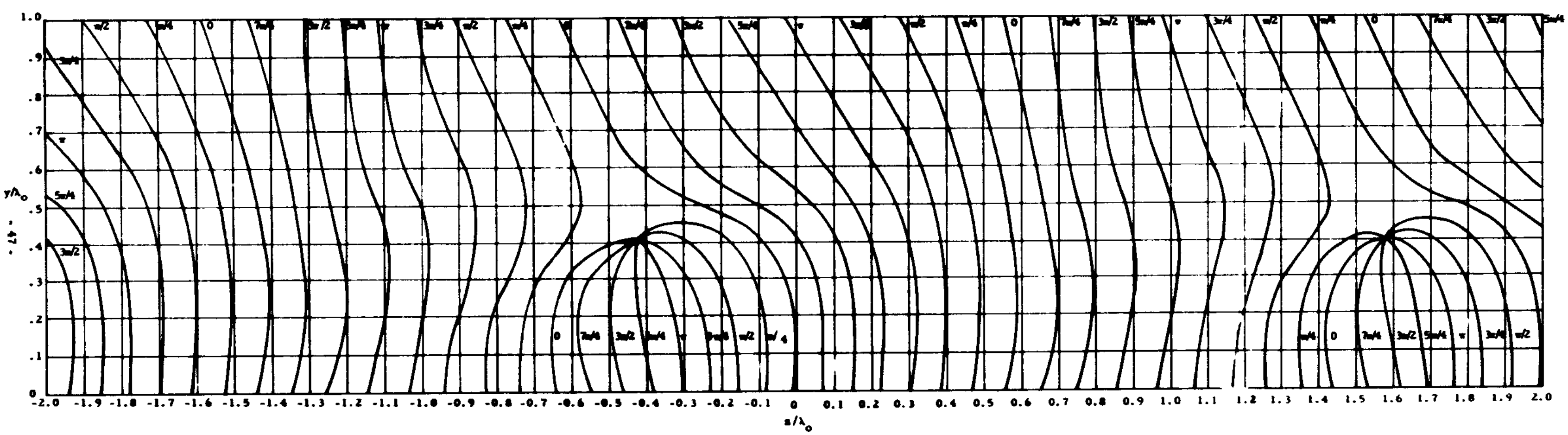

FIGURE 8. Phase of E_z in Near Field

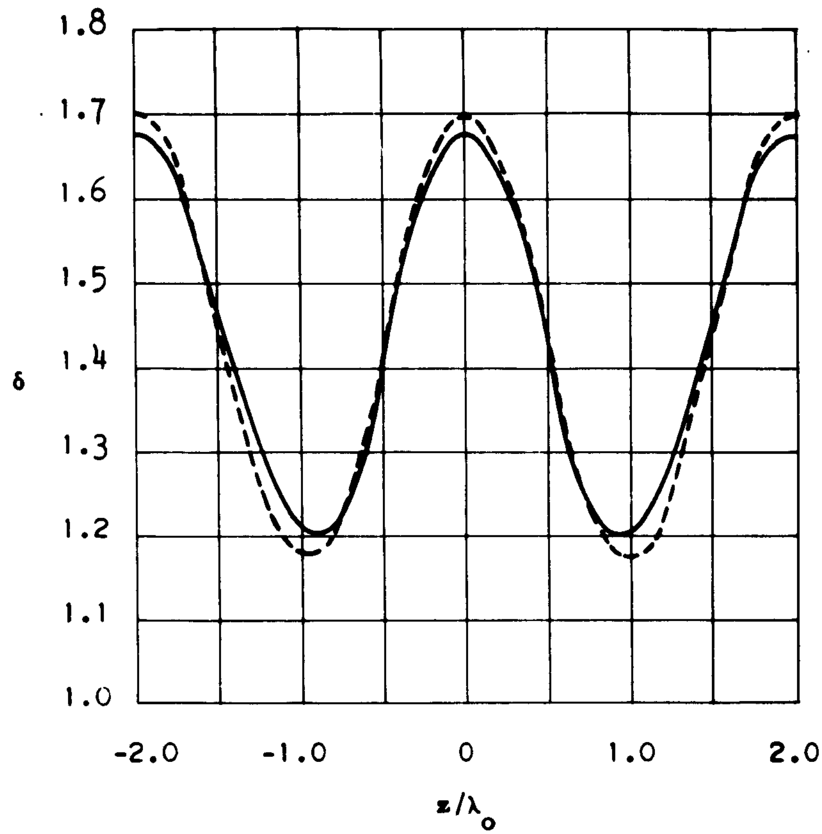

FIGURE 9. Relative Wave Number versus z/λ_o for H_x, E_y, and E_z.

---------- δ_{E_y}

———— $\delta_{E_z} = \delta_{H_x}$

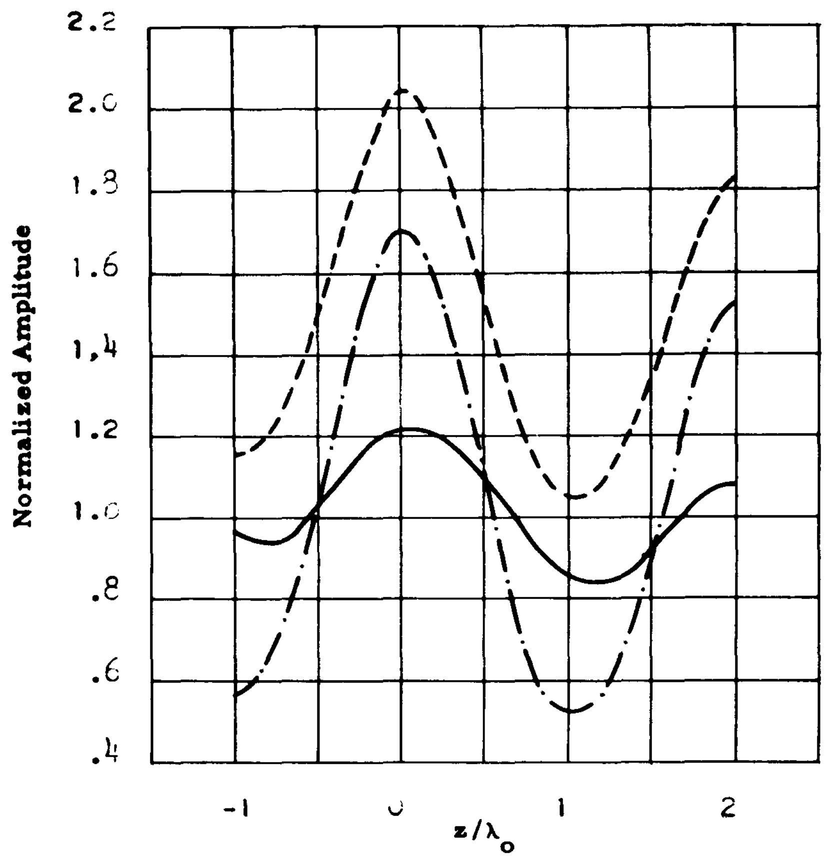

FIGURE 10. Amplitude vs z/λ_o.

H_x

$\frac{\omega\epsilon}{k} E_y$

$\frac{\omega\epsilon}{k} E_z$

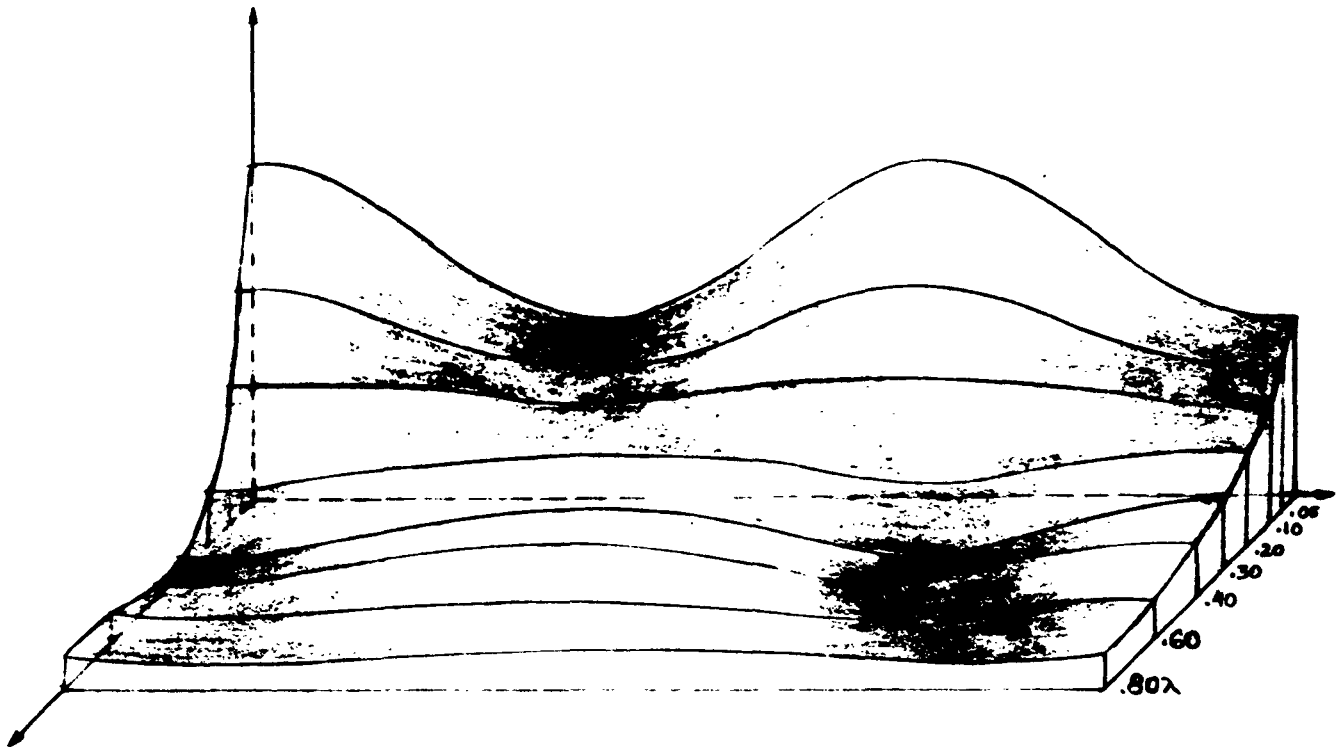

FIGURE 11. Sketch of Amplitude of E_y.

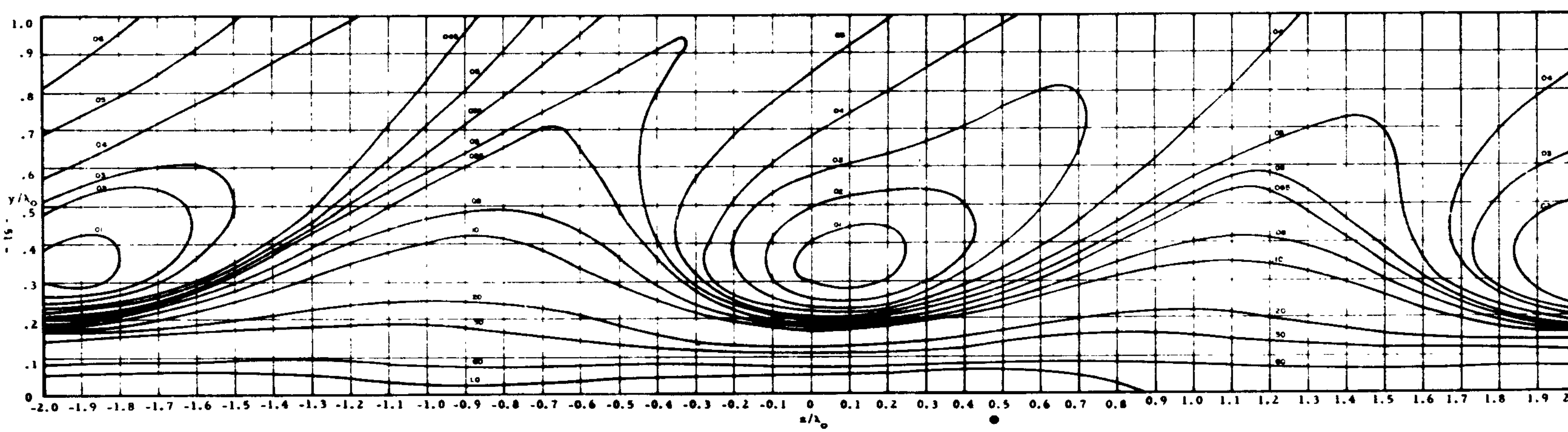

FIGURE 12. Amplitude of the Poynting Vector

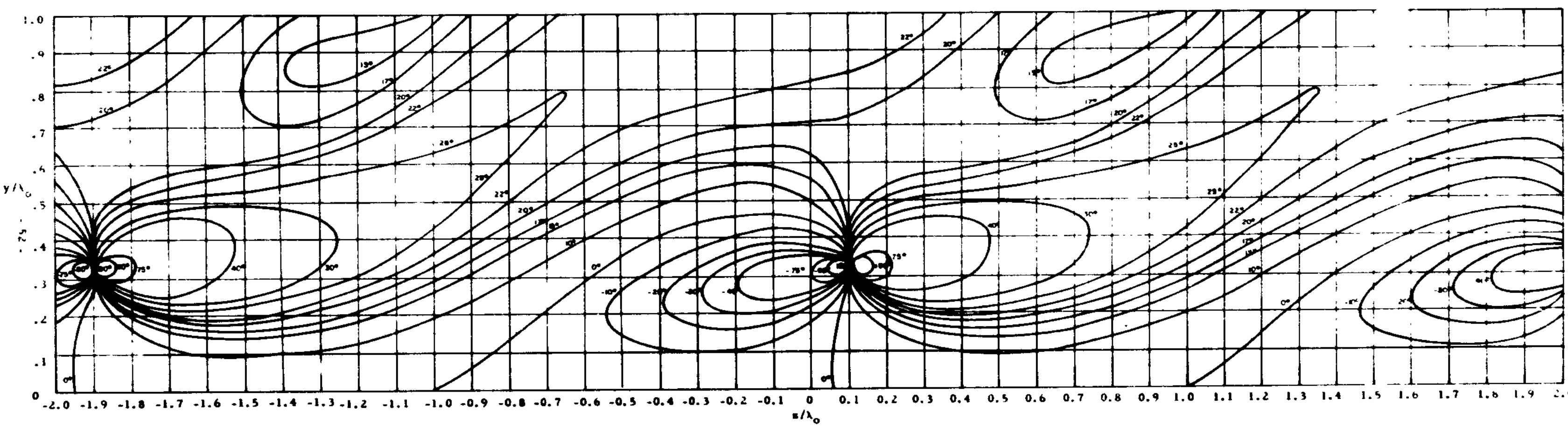

FIGURE 13. Orientation of the Poynting Vector in Degrees with the Positive Direction of the Z-Axis Taken as Reference (0°)

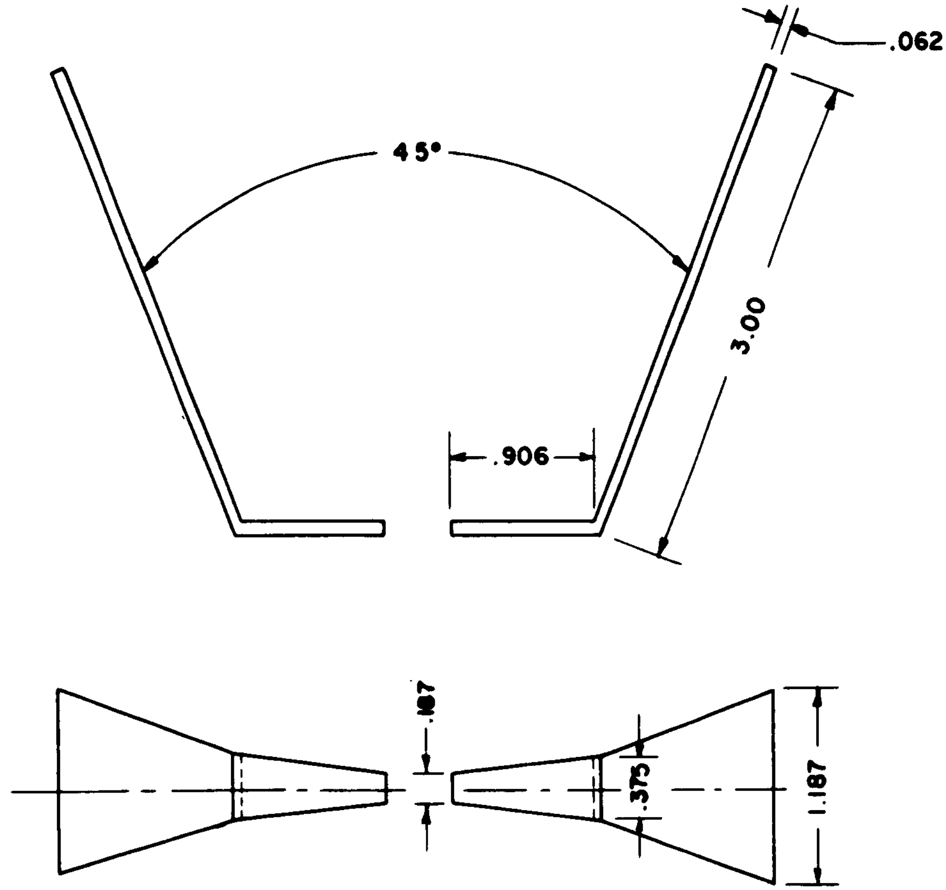

FIGURE 14. Rabbit Ear Feed.

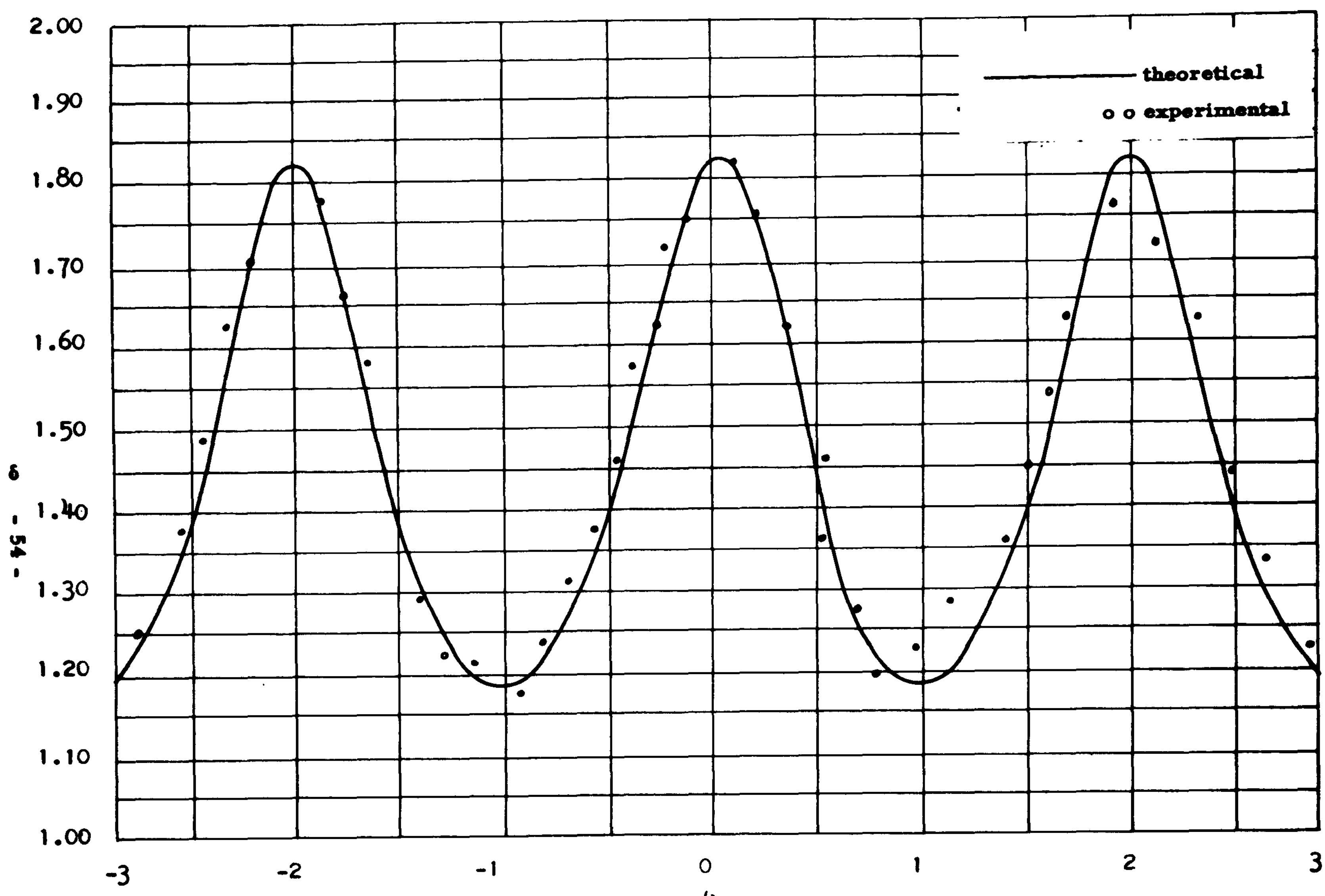

FIGURE 15. Theoretical and experimental δ vs z/λ_o of modulated Yagi at $y=0.2\lambda$.

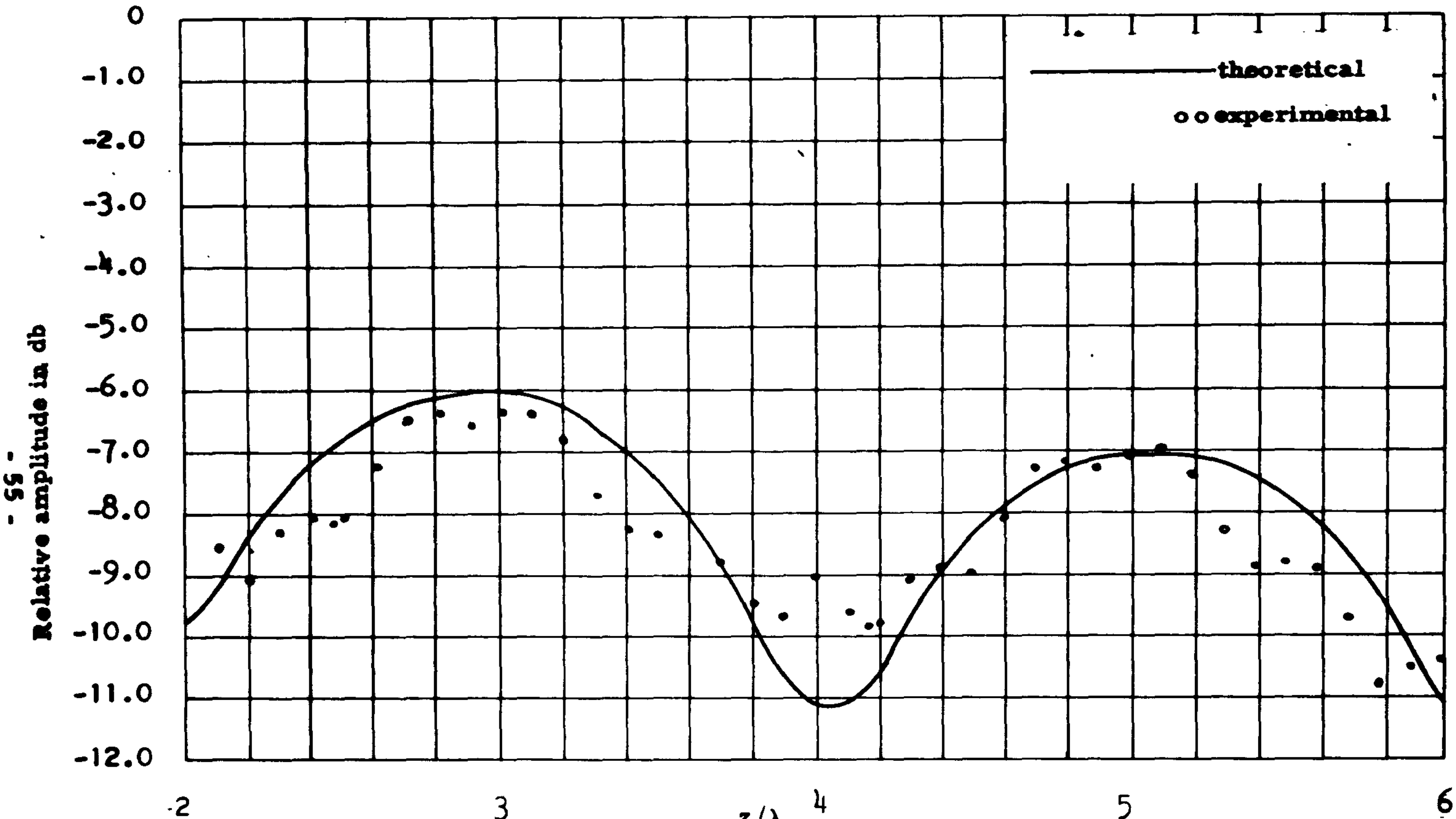

FIGURE 16. Theoretical and experimental relative amplitude of E_y vs z/λ_o for $y = 0.2\lambda$.

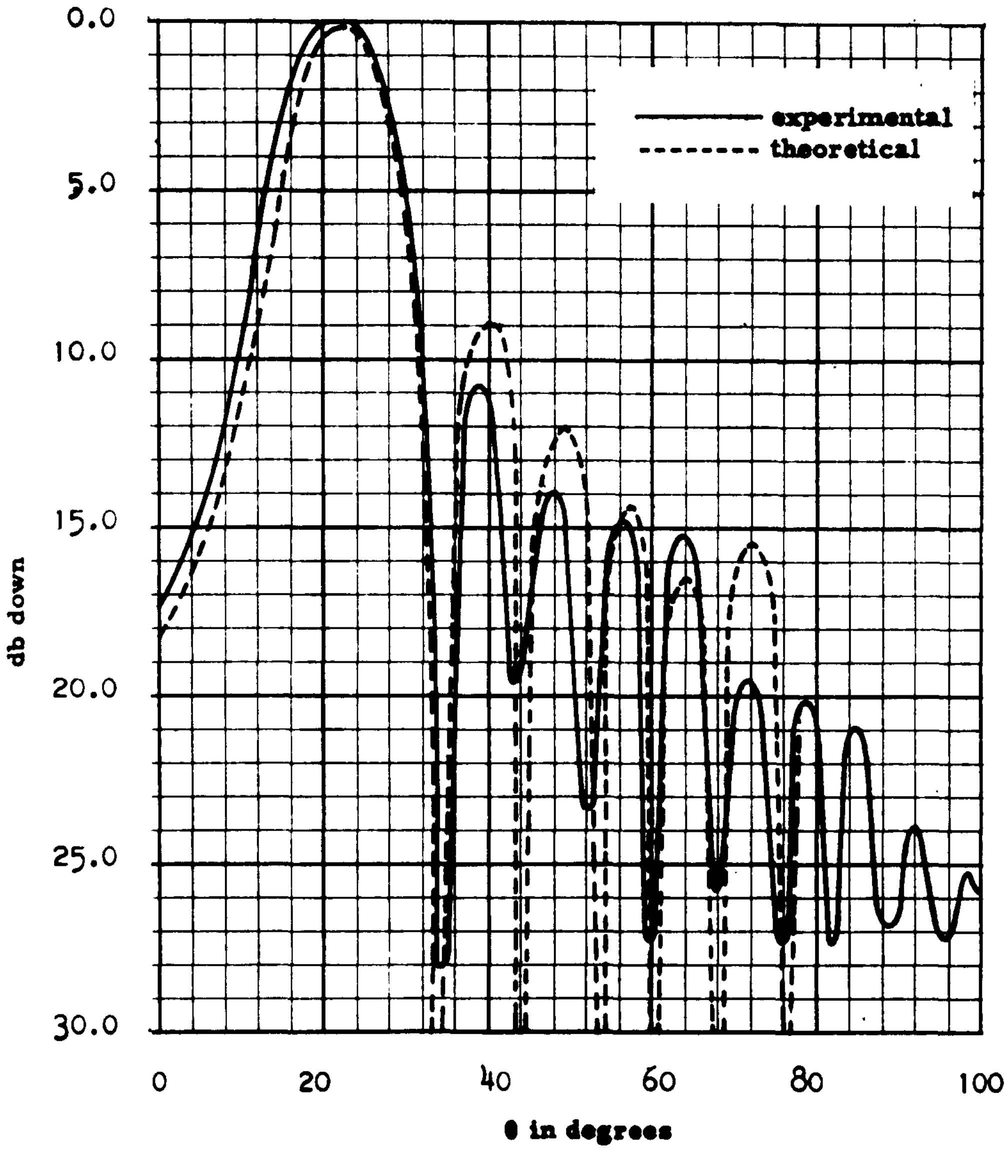

FIGURE 17. Approximation Theoretical pattern vs Experimental Radiation pattern of modulated 9λ Yagi.

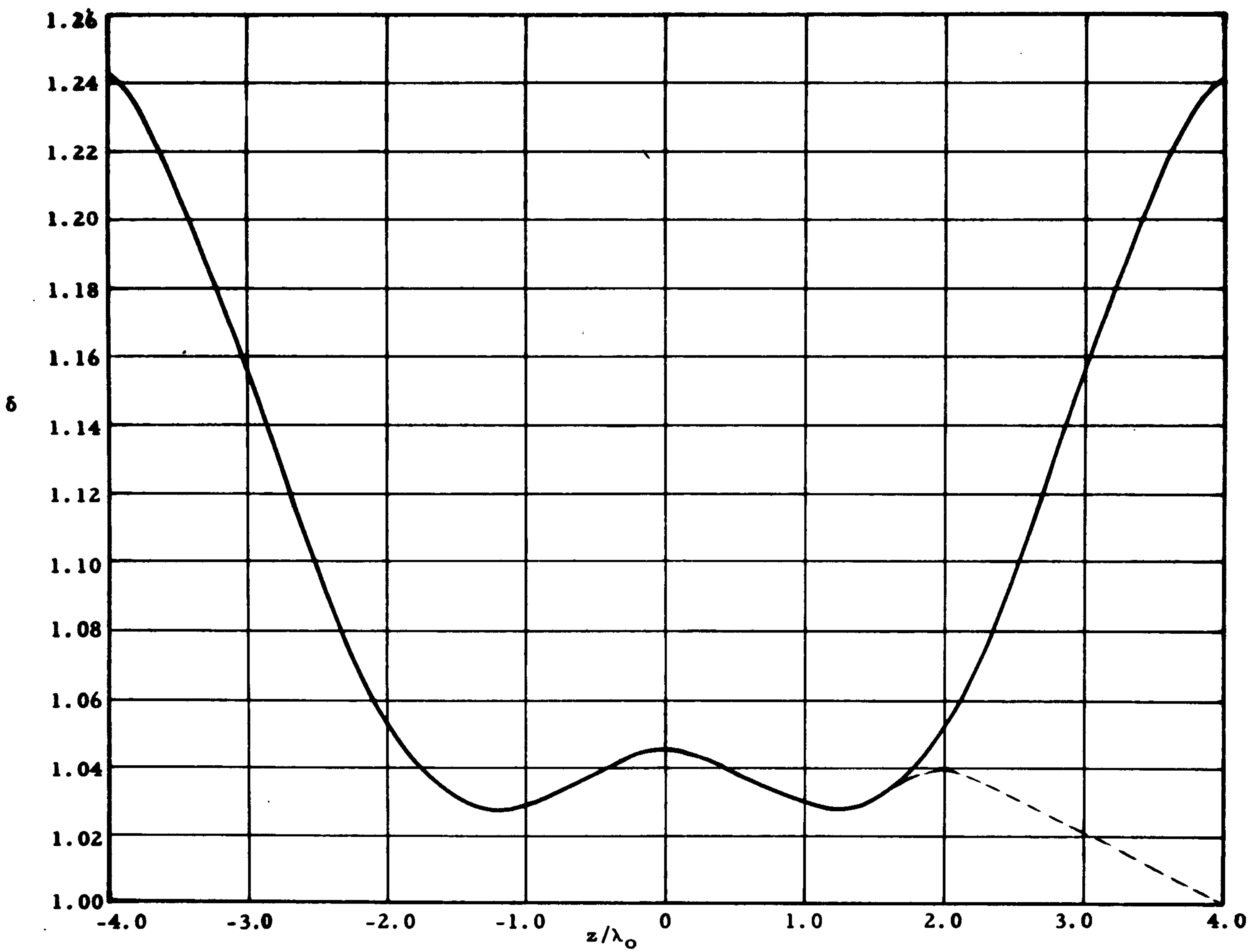

Figure 18. Relative Wave number versus Distance for an 8λ Array.

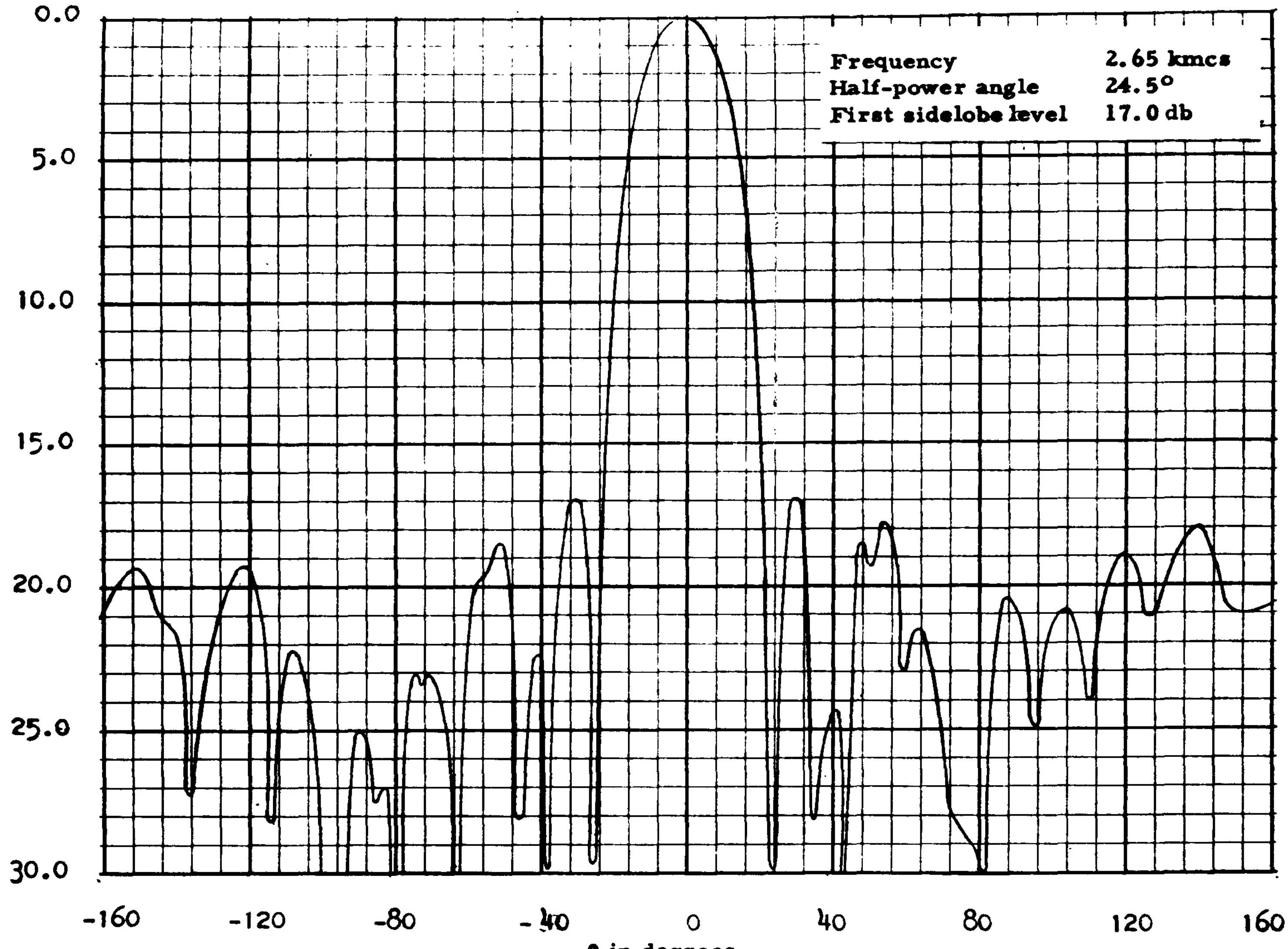

FIGURE 19. **Re plotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.**

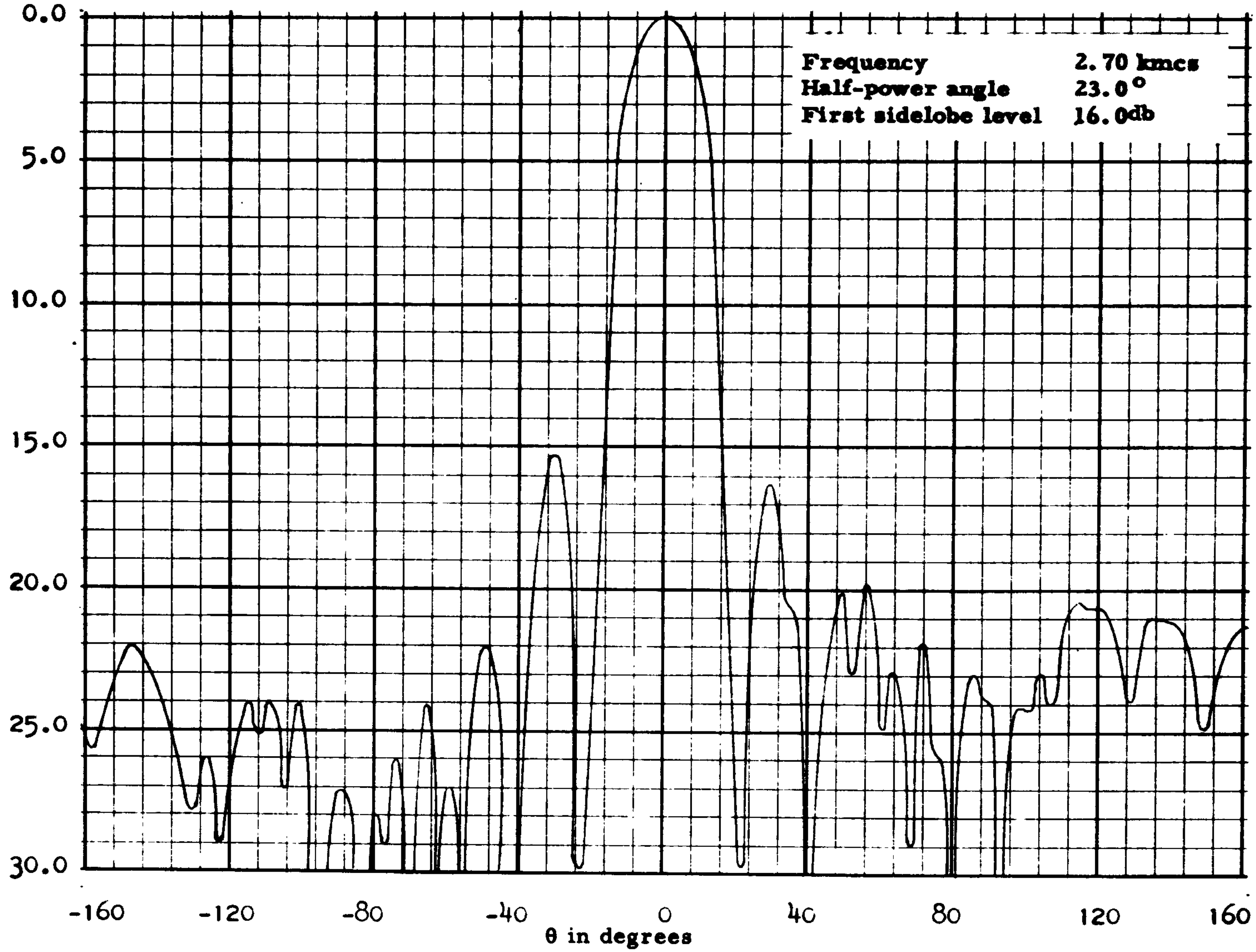

FIGURE 20. Re plotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

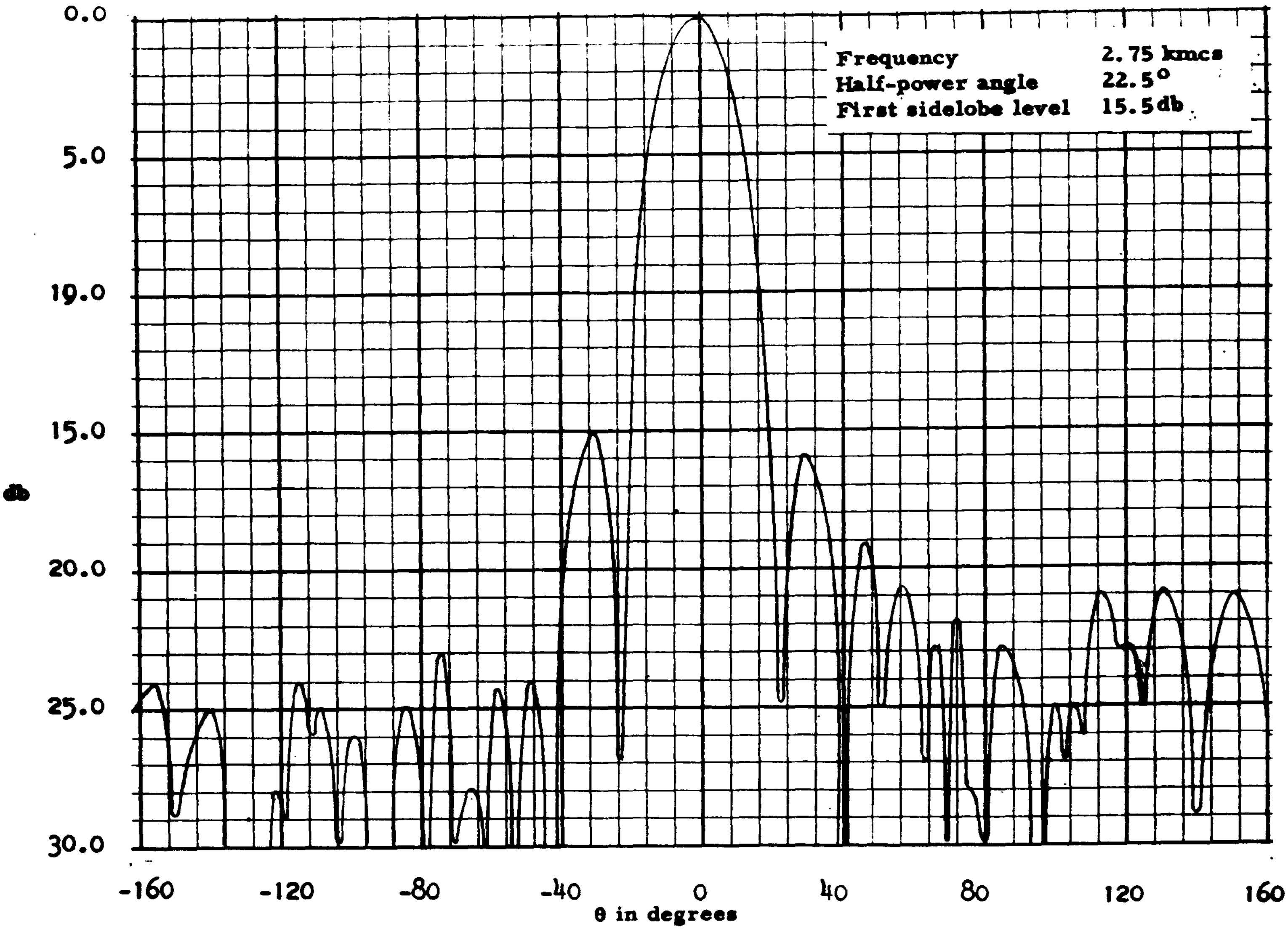

FIGURE 21. Replotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

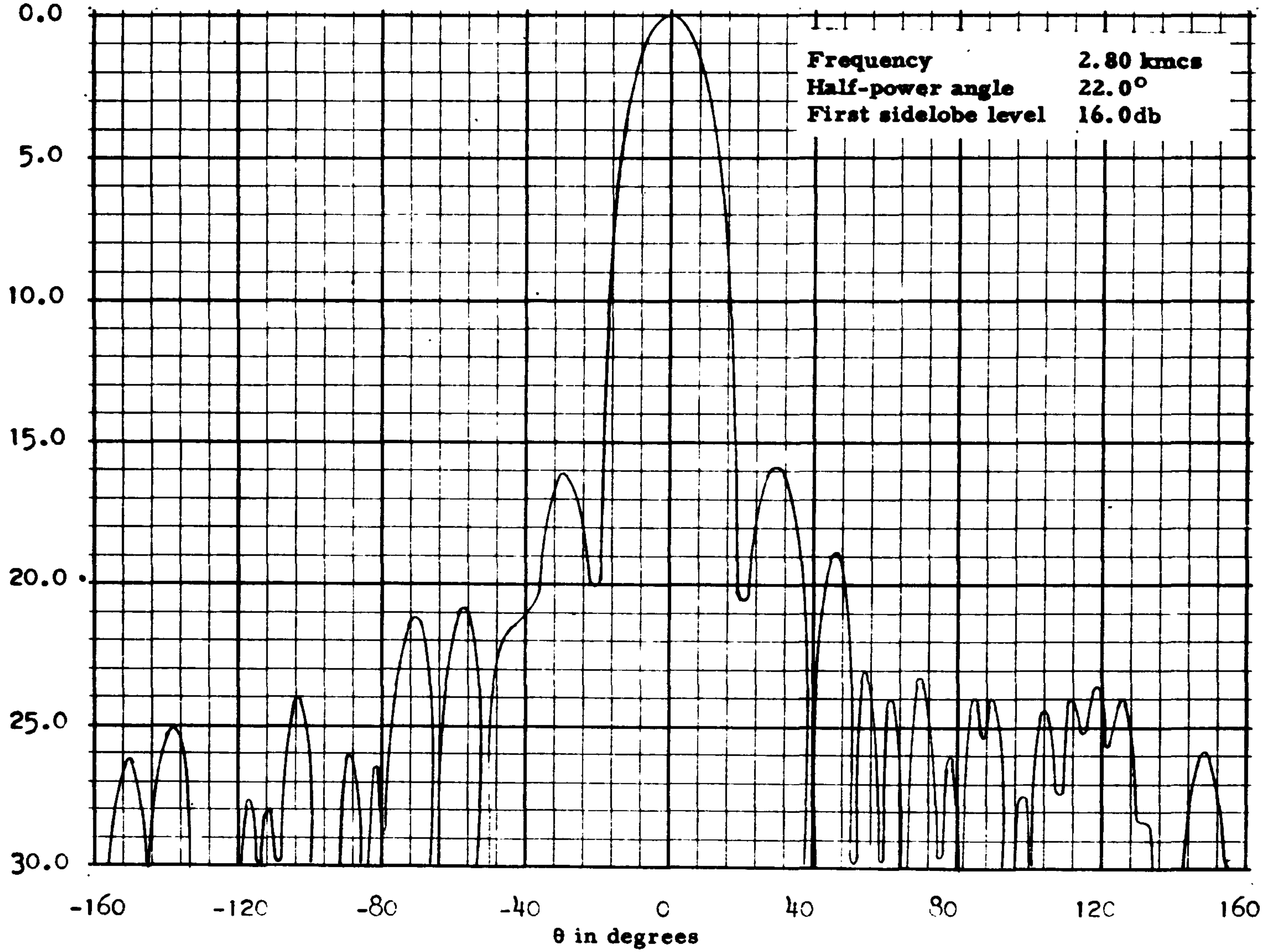

FIGURE 22. Replotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

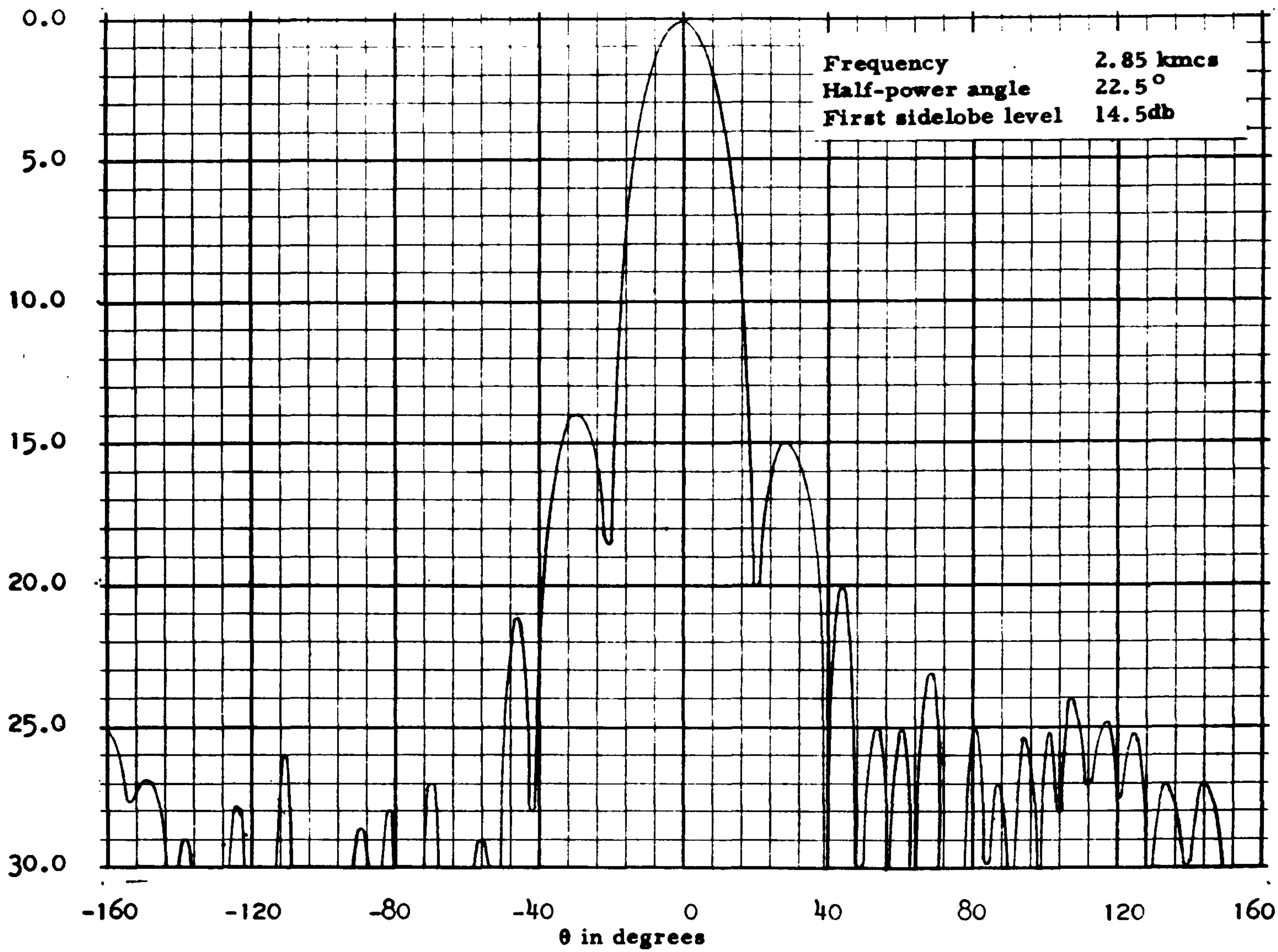

FIGURE 23. Replotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

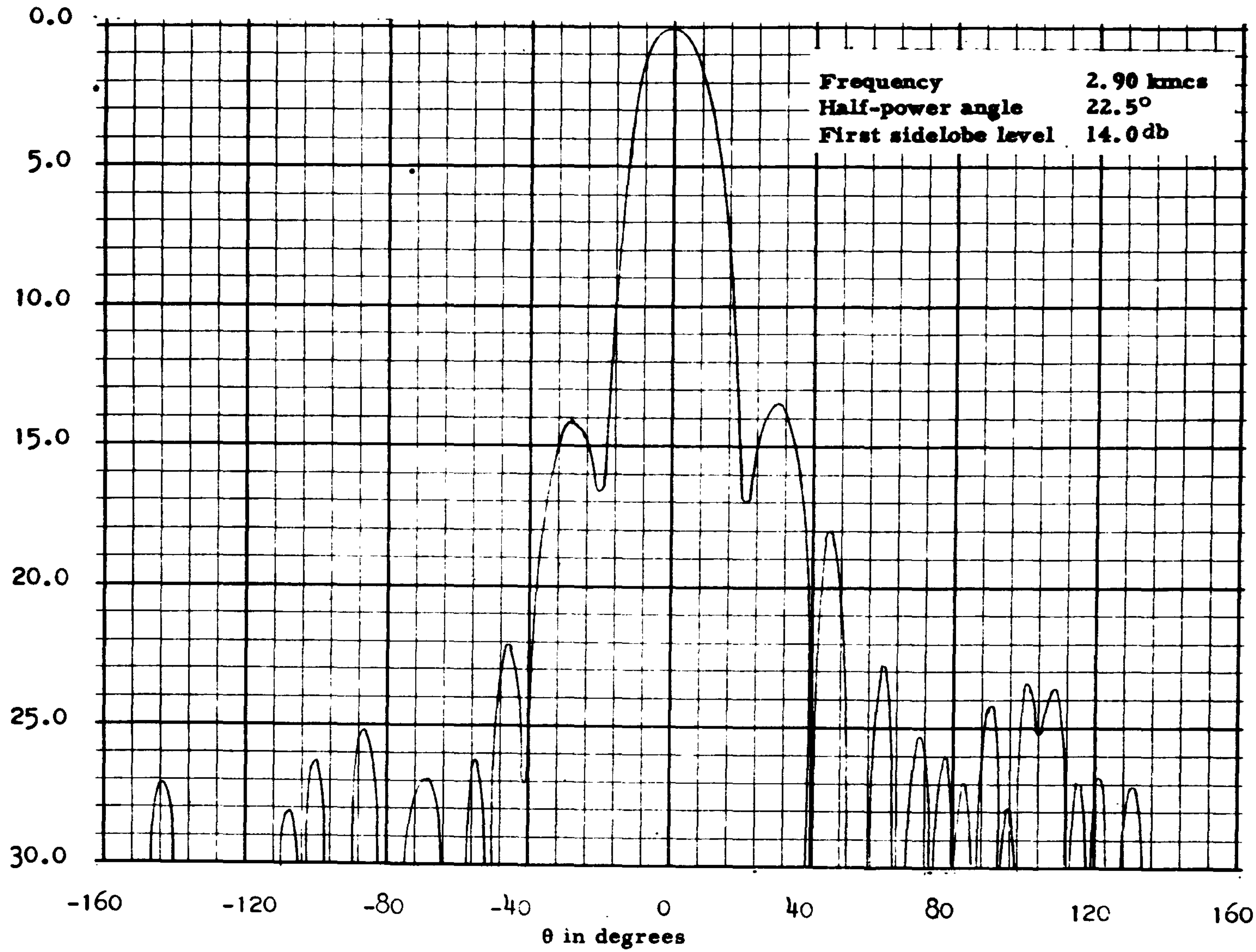

FIGURE 24. Replotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

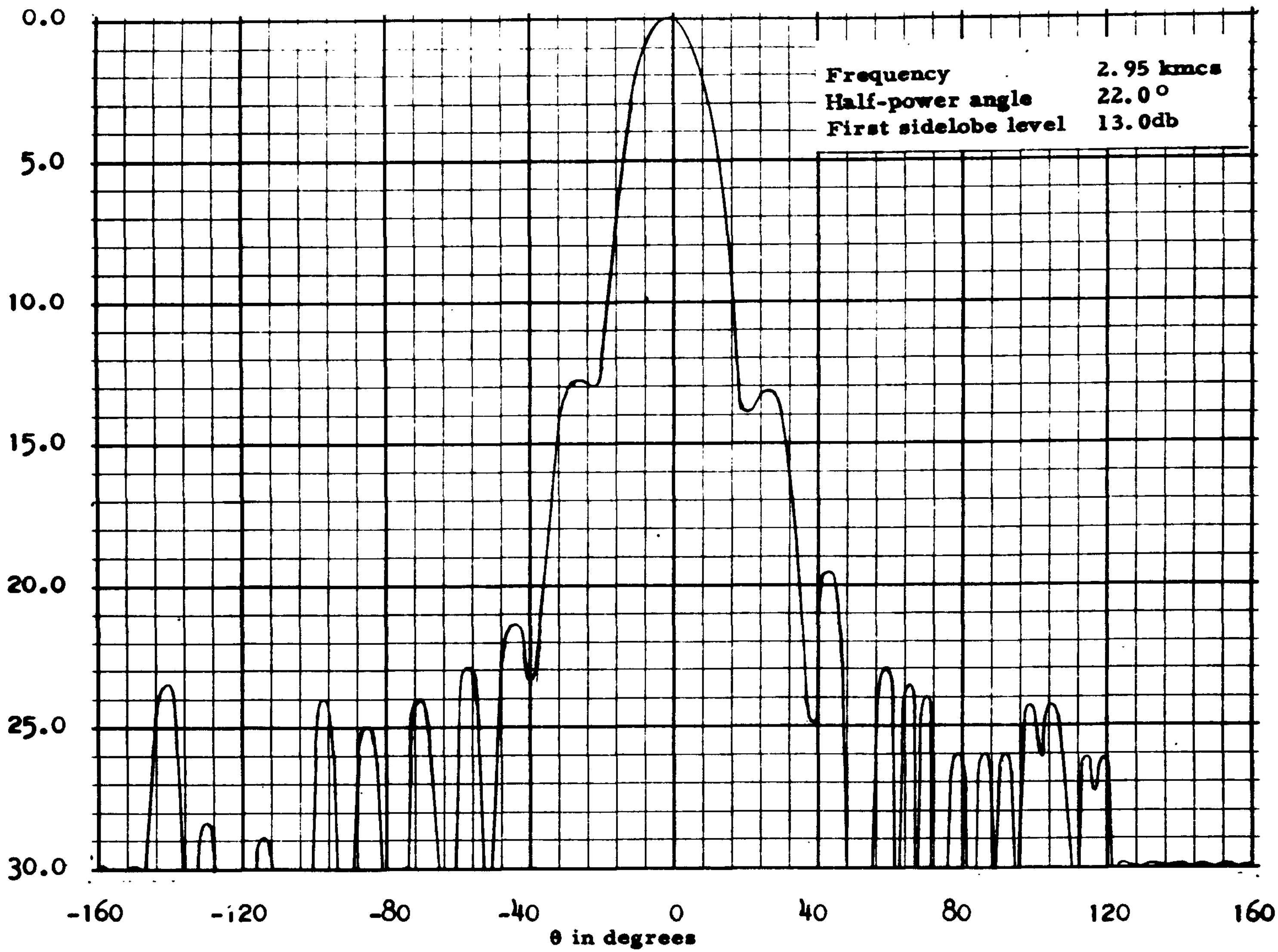

FIGURE 25. Replotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

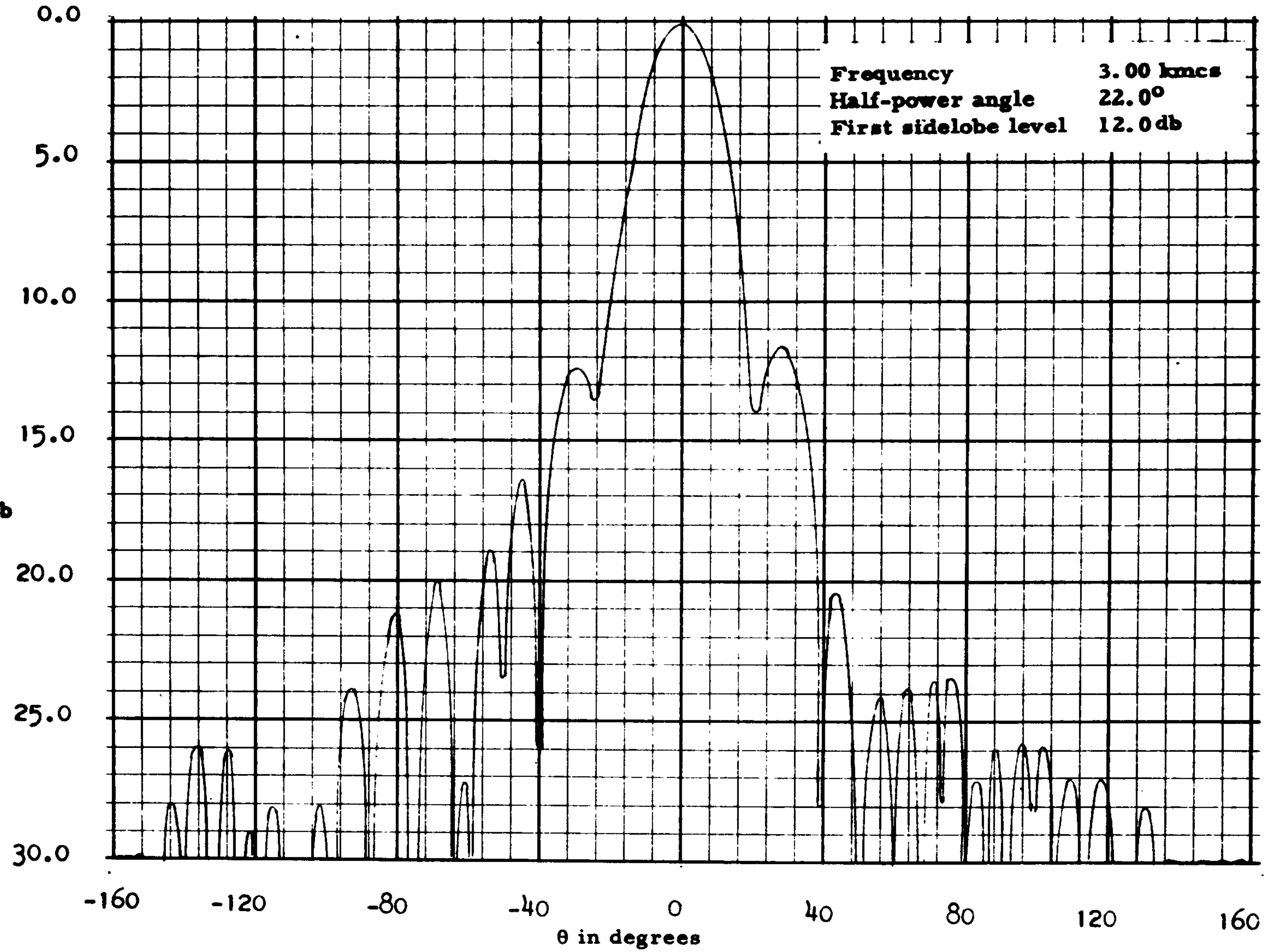

FIGURE 26. Replotted Radiation patterns of 8λ Yagi as per distribution of Figure 18 with dotted line.

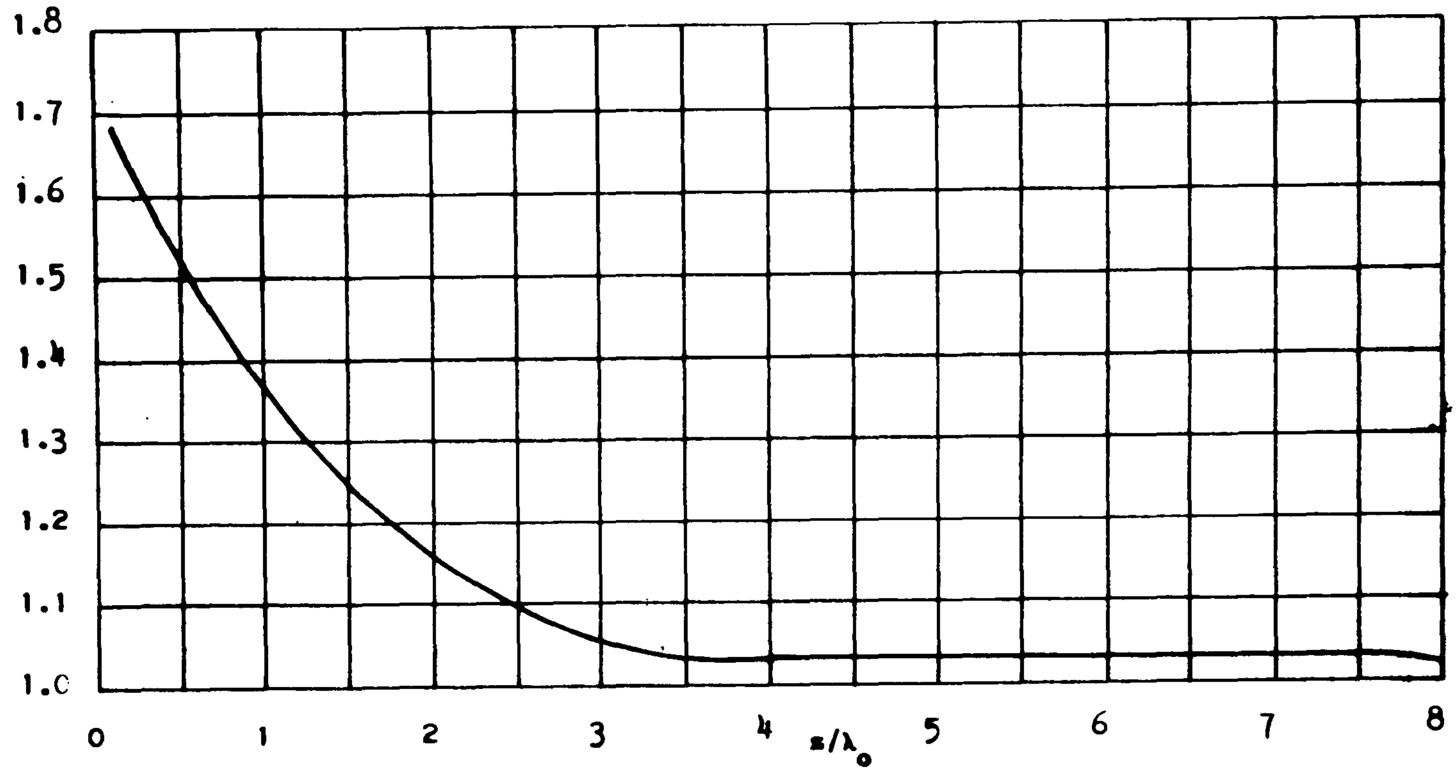

FIGURE 27. Relative wave number vs distance for 8λ endfire array.

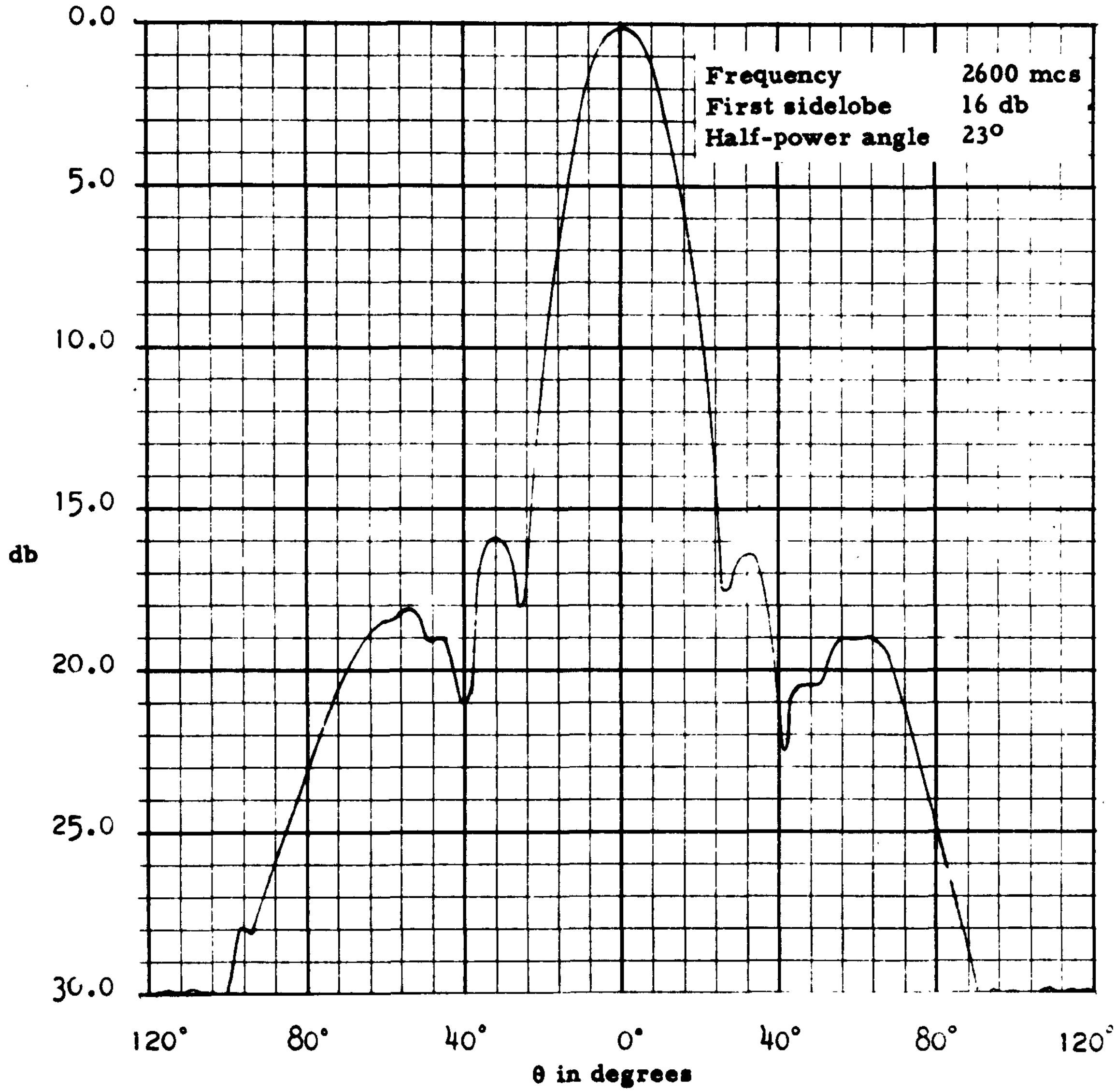

FIGURE 28. **Replotted radiation pattern for δ of array given in Figure 27.**

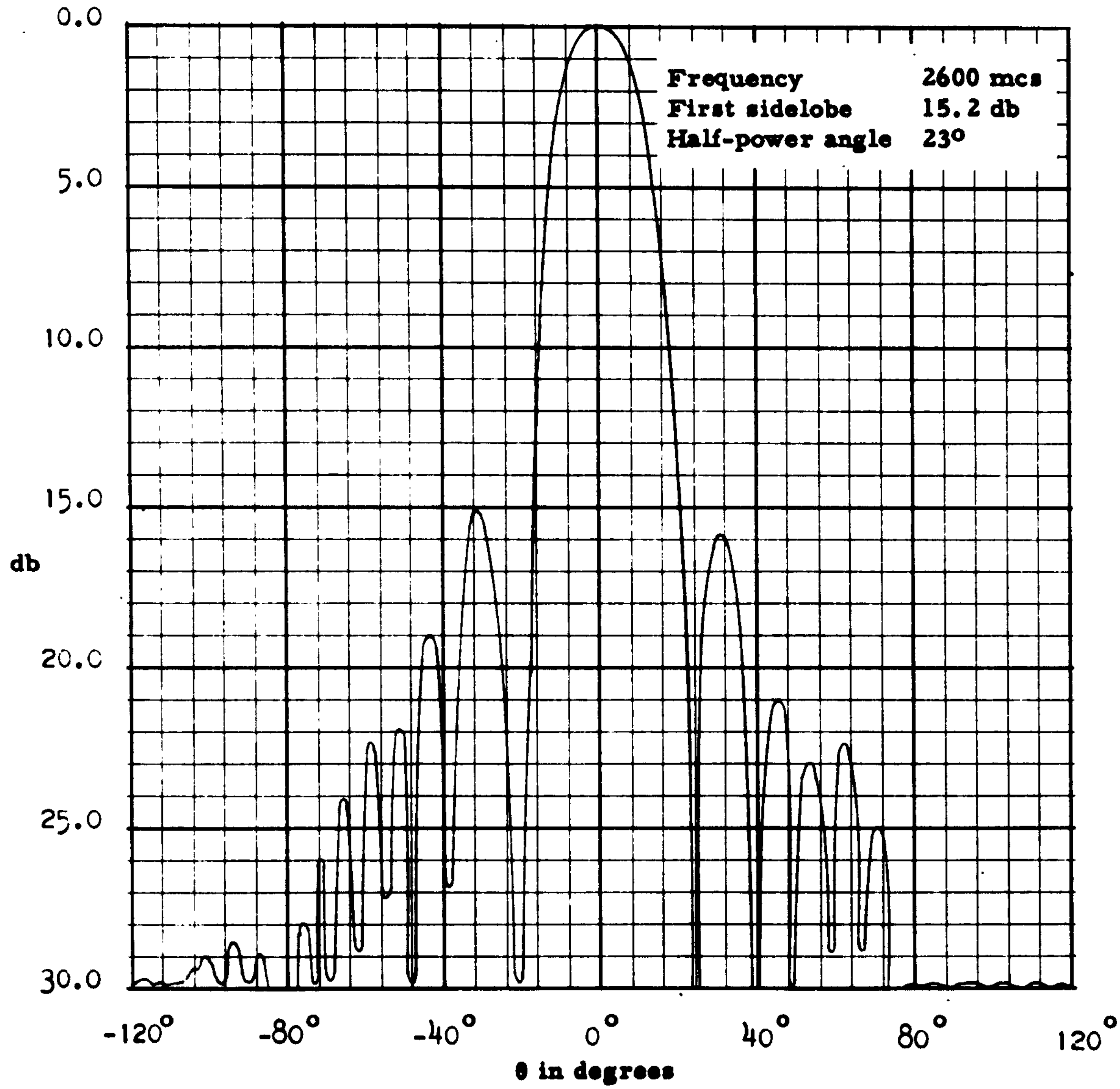

FIGURE 29. Replotted radiation pattern for δ of array given in Figure 27.

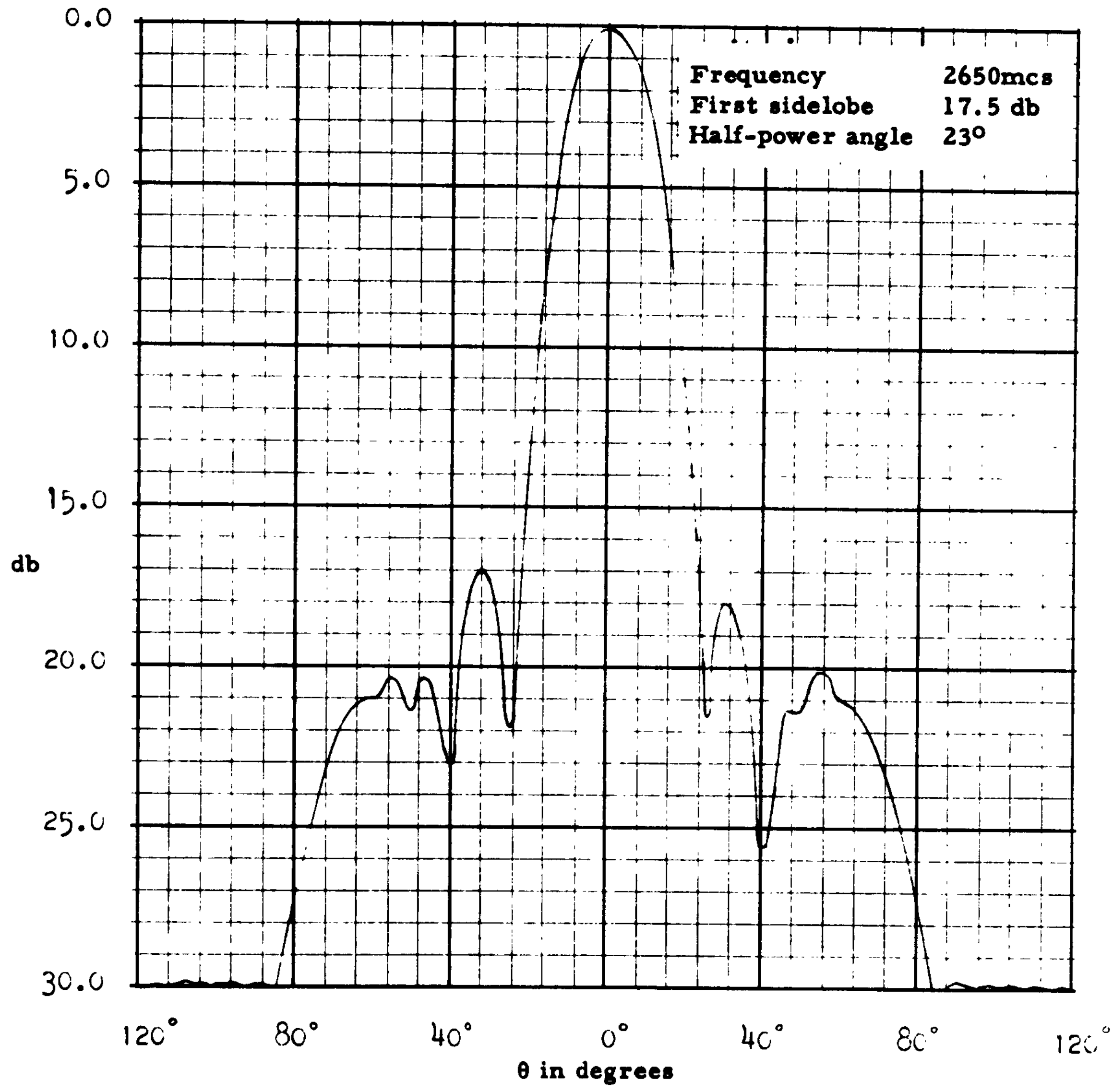

FIGURE 30. Replotted radiation pattern for δ of array given in Figure 27.

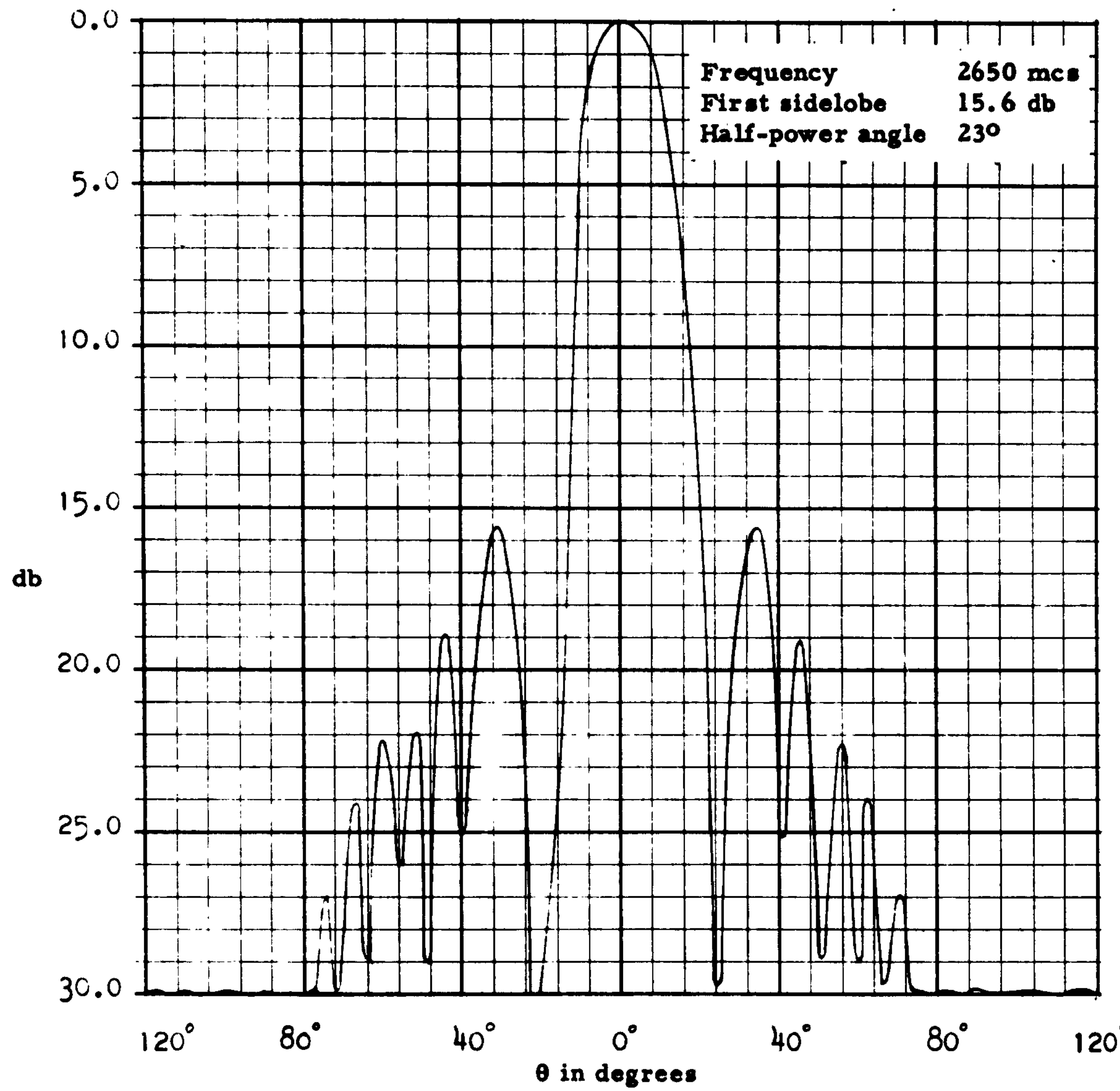

FIGURE 31. Replotted radiation pattern for δ of array given in Figure 27.

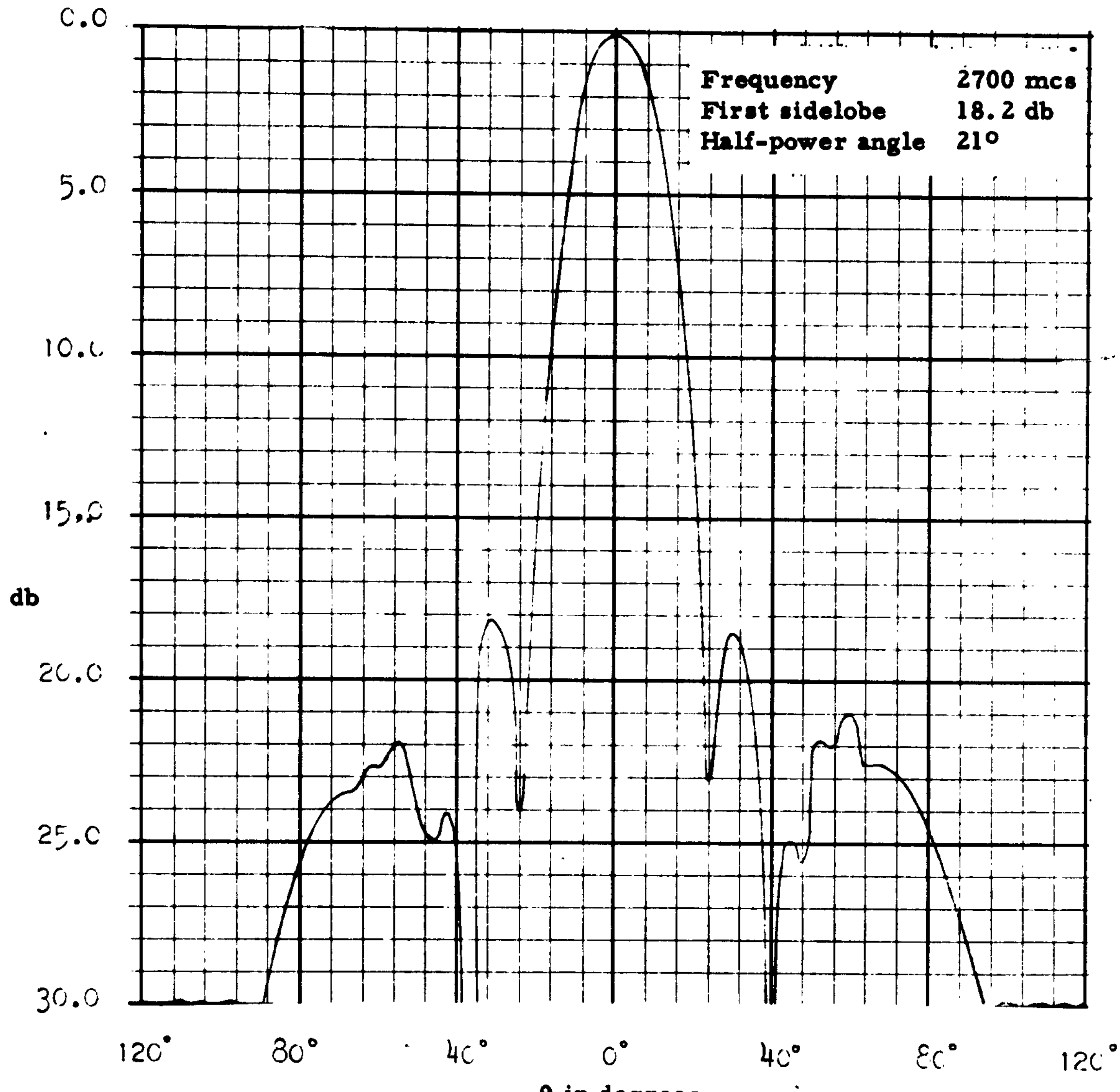

FIGURE 32. **Replotted radiation pattern for δ of array given in Figure 27.**

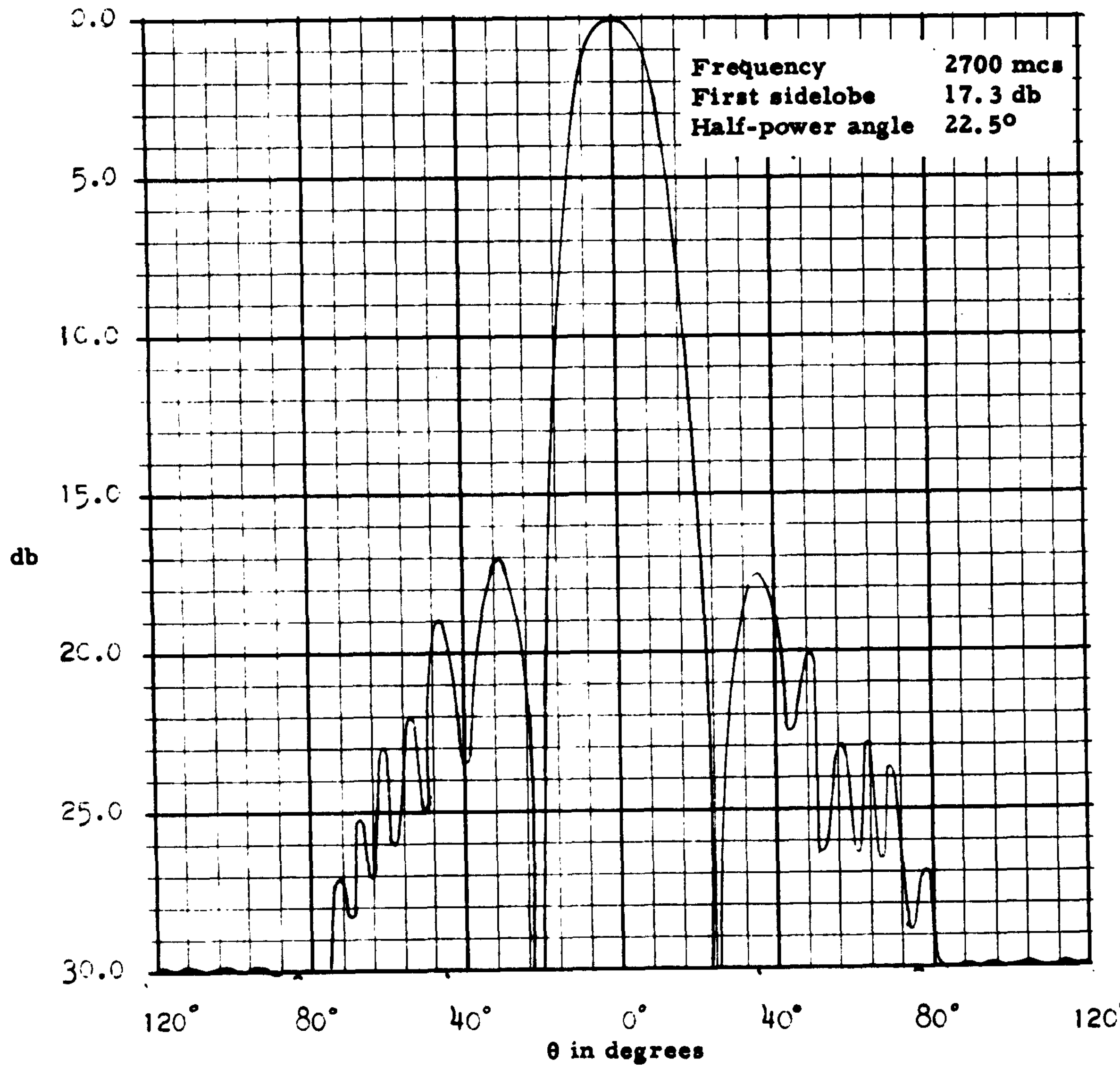

FIGURE 33. Replotted radiation pattern for δ of array given in Figure 27.

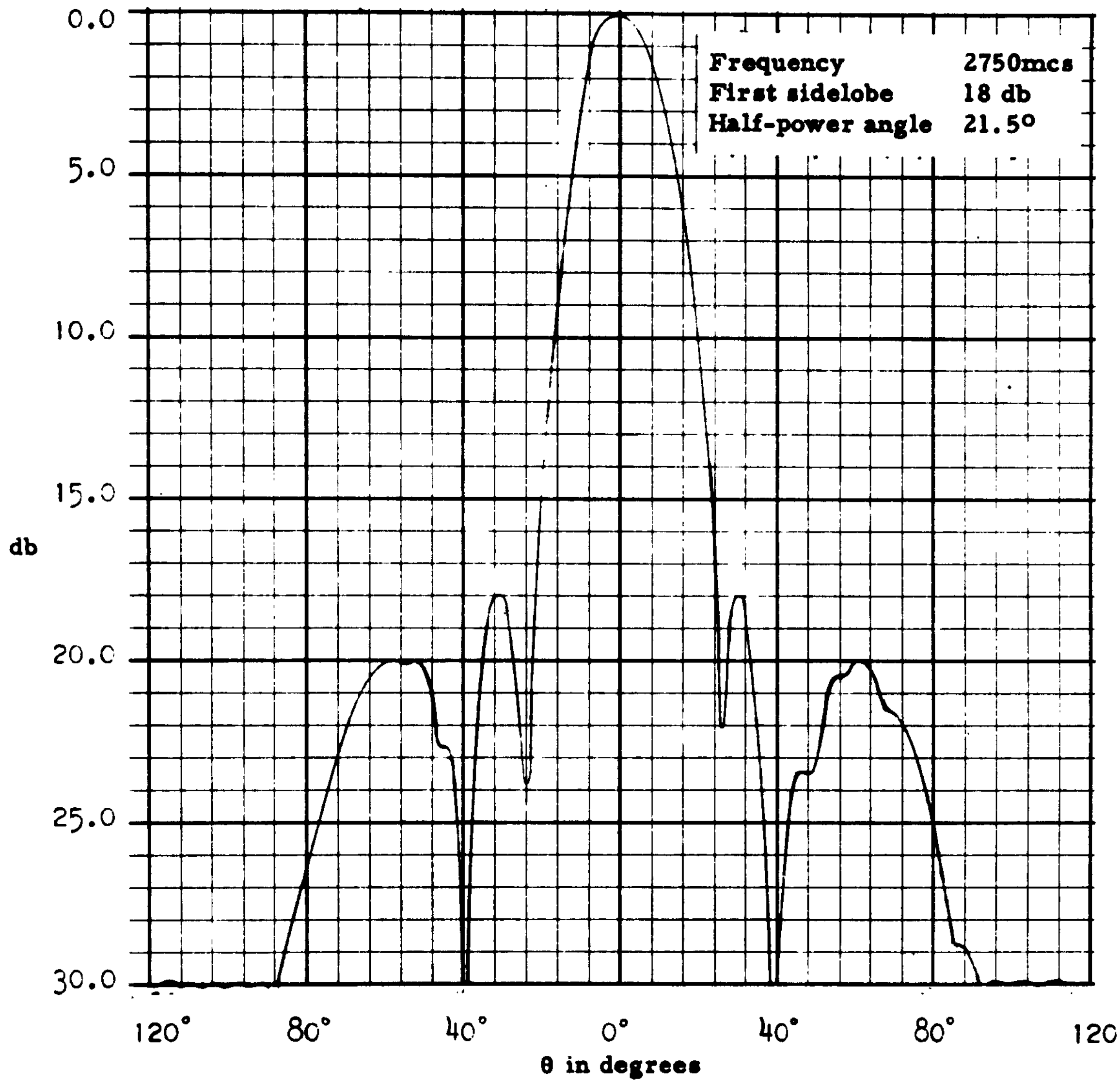

FIGURE 34. Replotted radiation pattern for δ of array given in Figure 27.

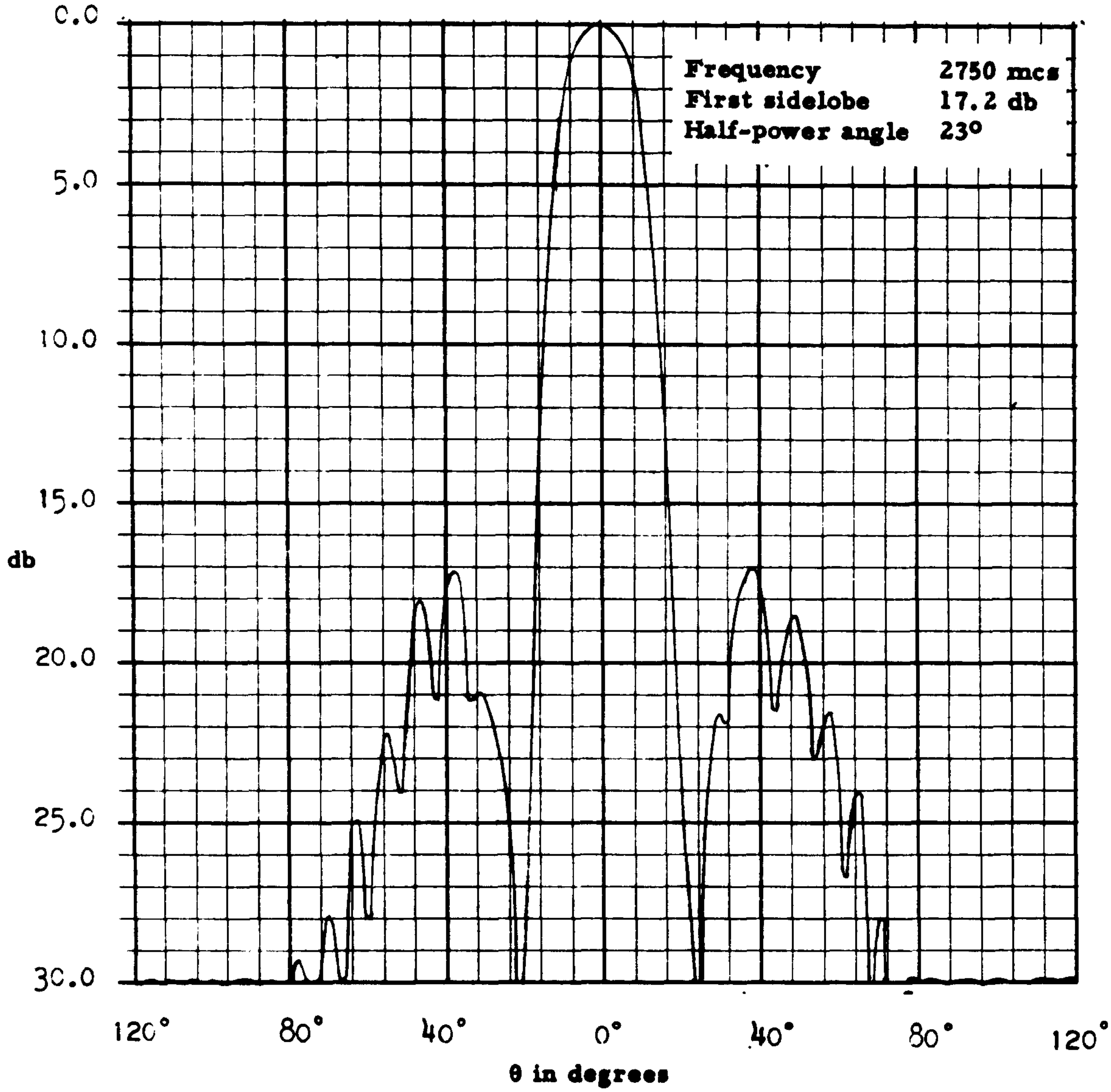

FIGURE 35. Replotted radiation pattern for δ of array given in Figure 27.

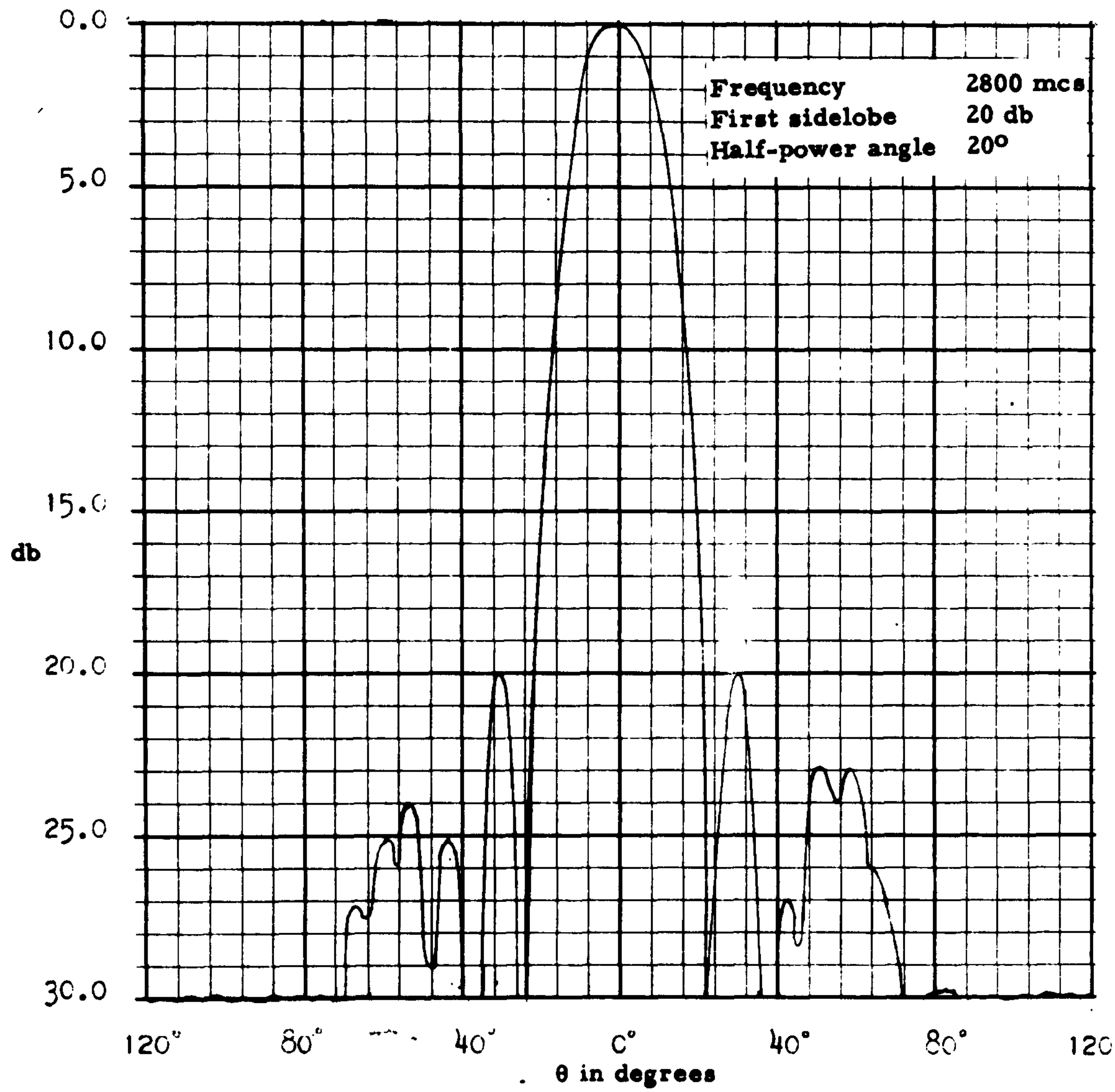

FIGURE 36. Replotted radiation pattern for δ of array given in Figure 27.

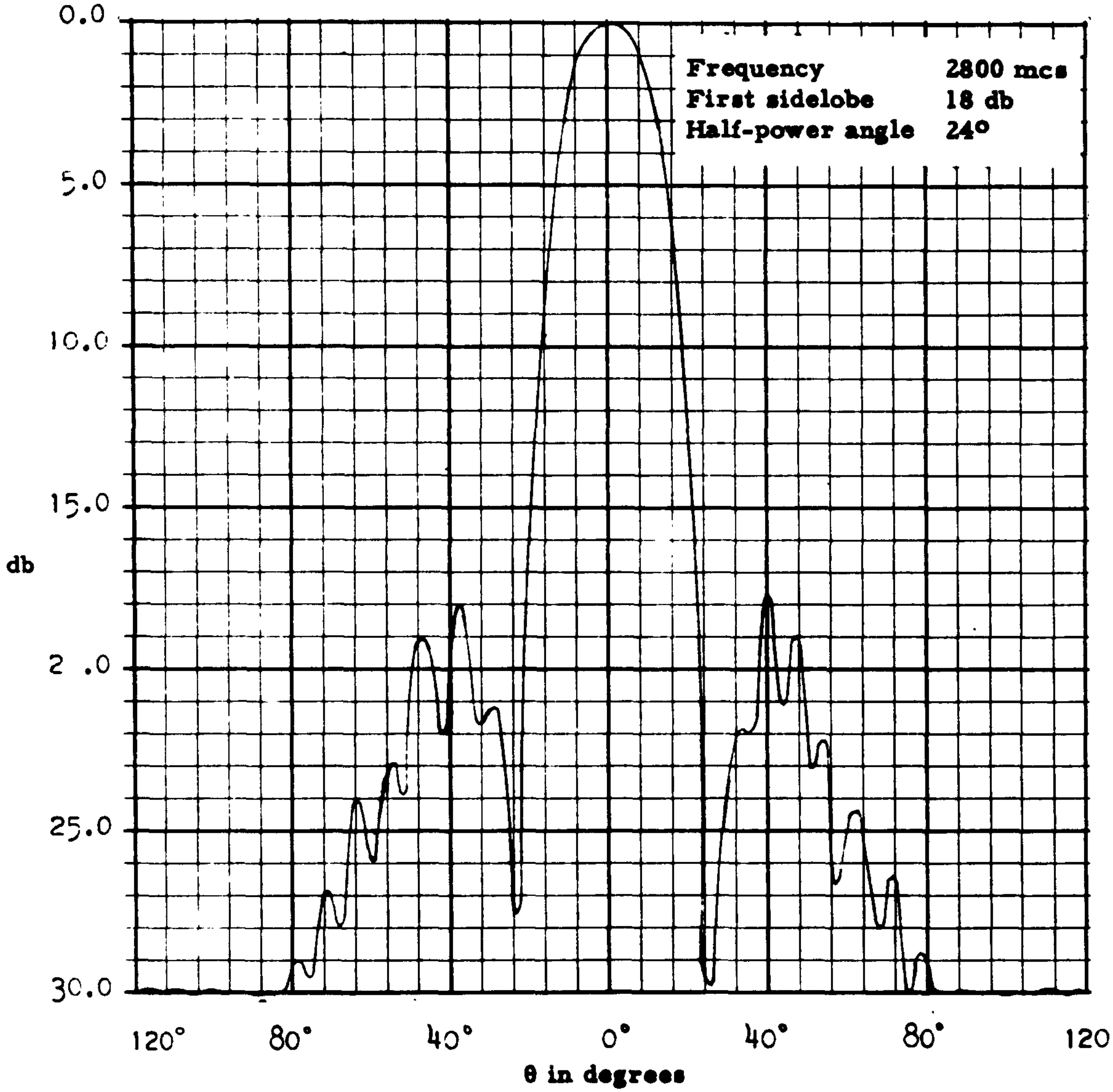

FIGURE 37. Replotted radiation pattern for δ of array given in Figure 27.

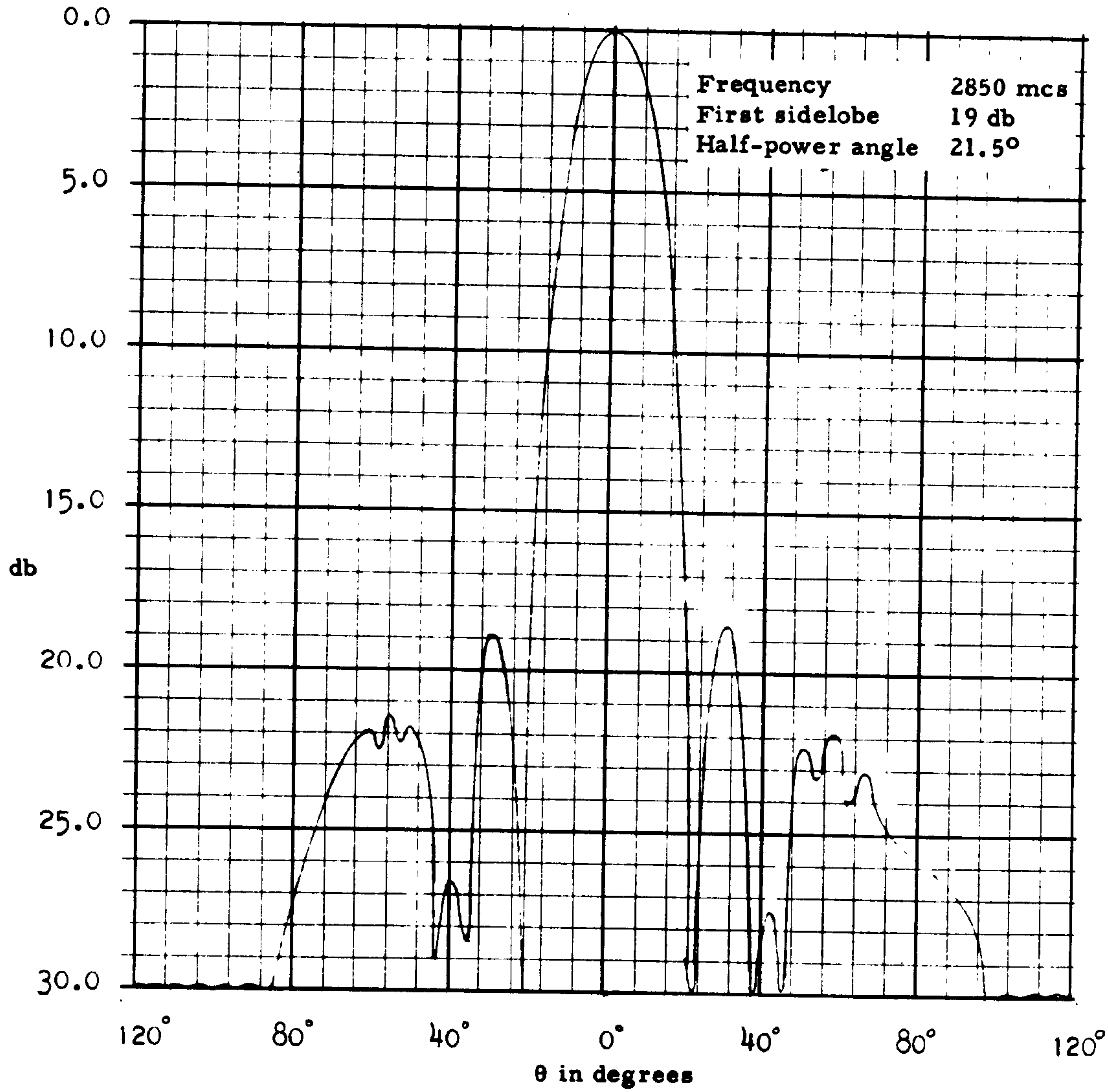

FIGURE 38. Replotted radiation pattern for δ of array given in Figure 27.

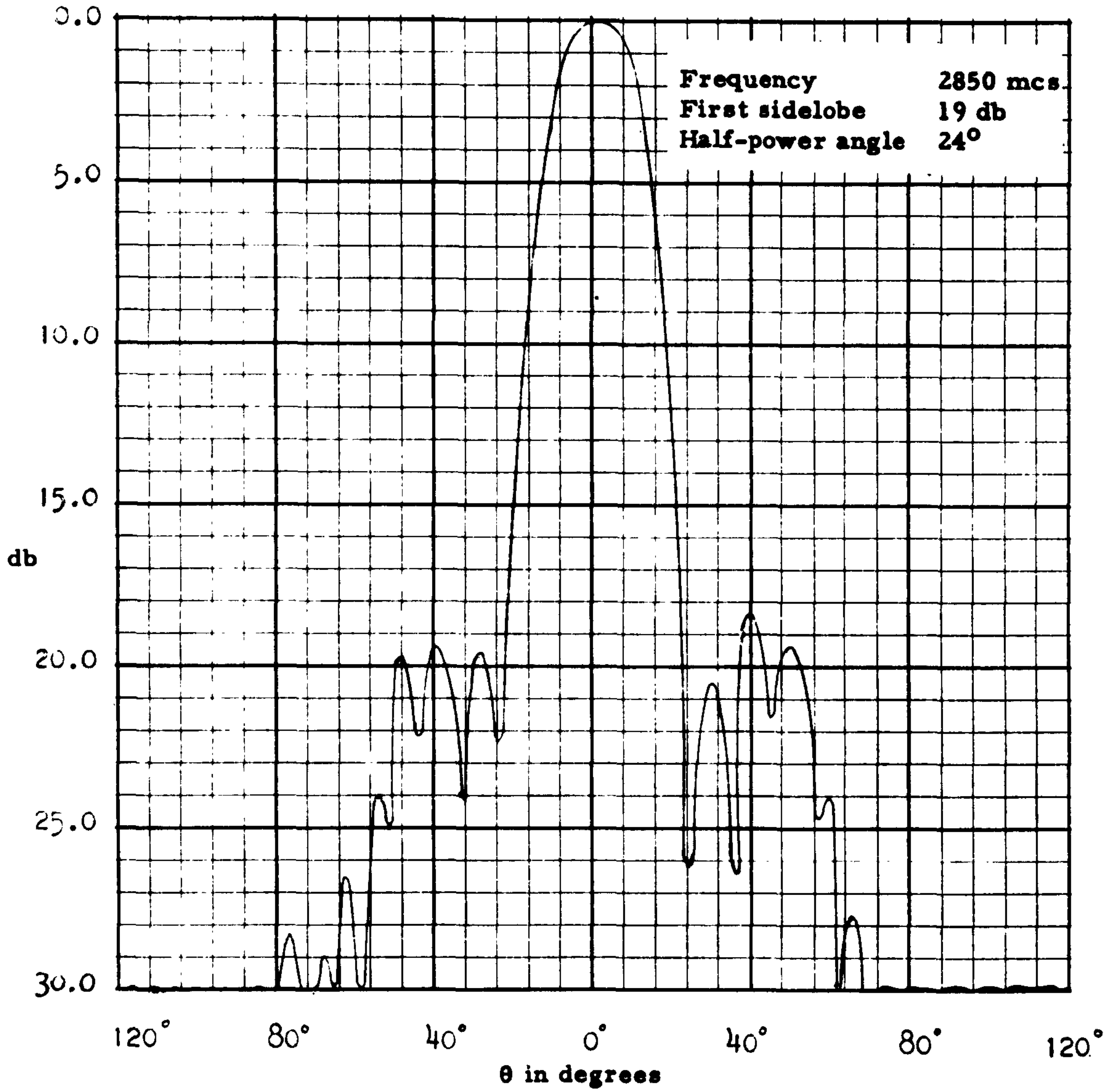

FIGURE 39. Replotted radiation pattern for δ of array given in Figure 27.

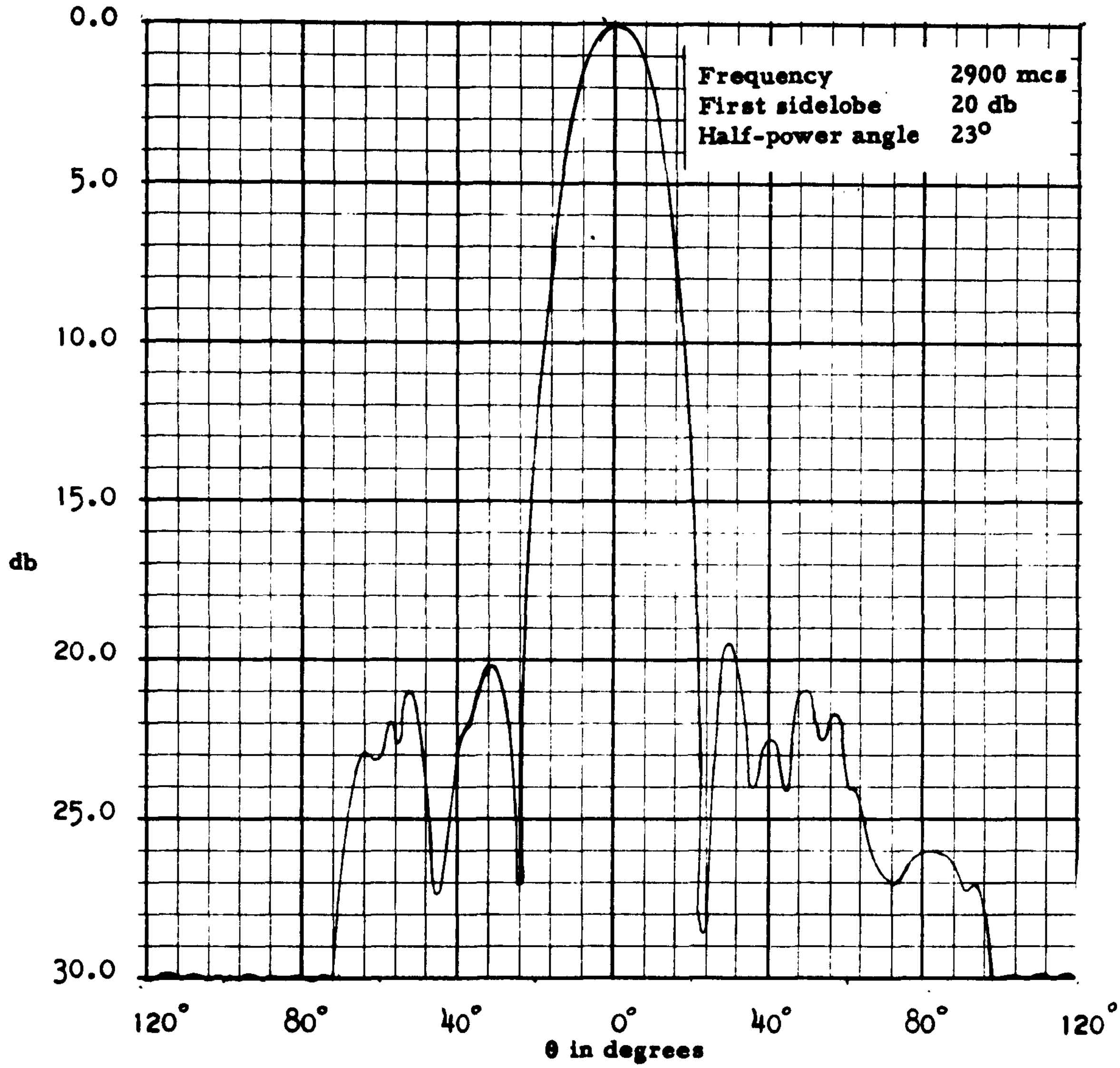

FIGURE 40. Replotted radiation pattern for δ of array given in Figure 27.

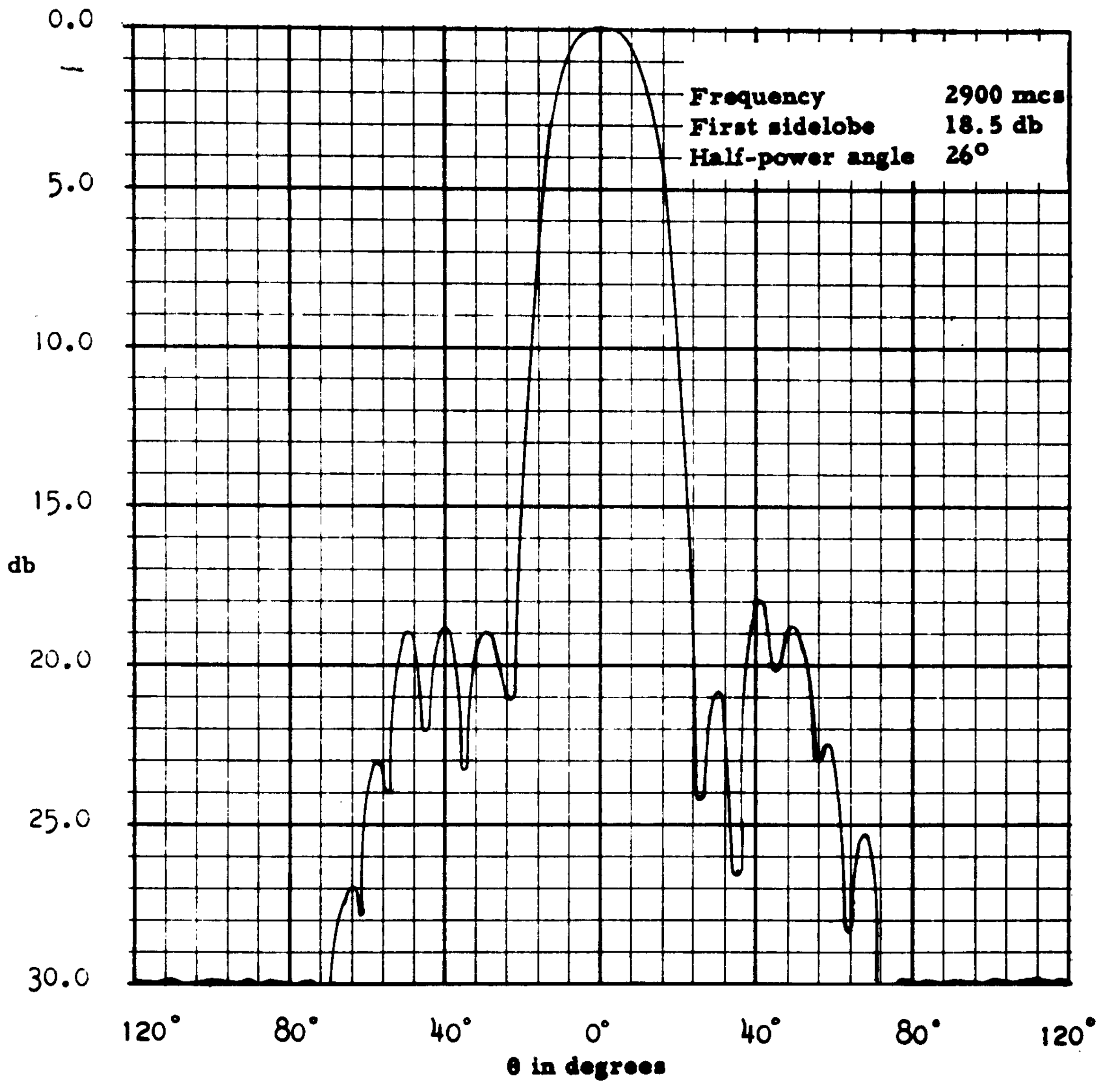

FIGURE 41. Replotted radiation pattern for δ of array given in Figure 27.

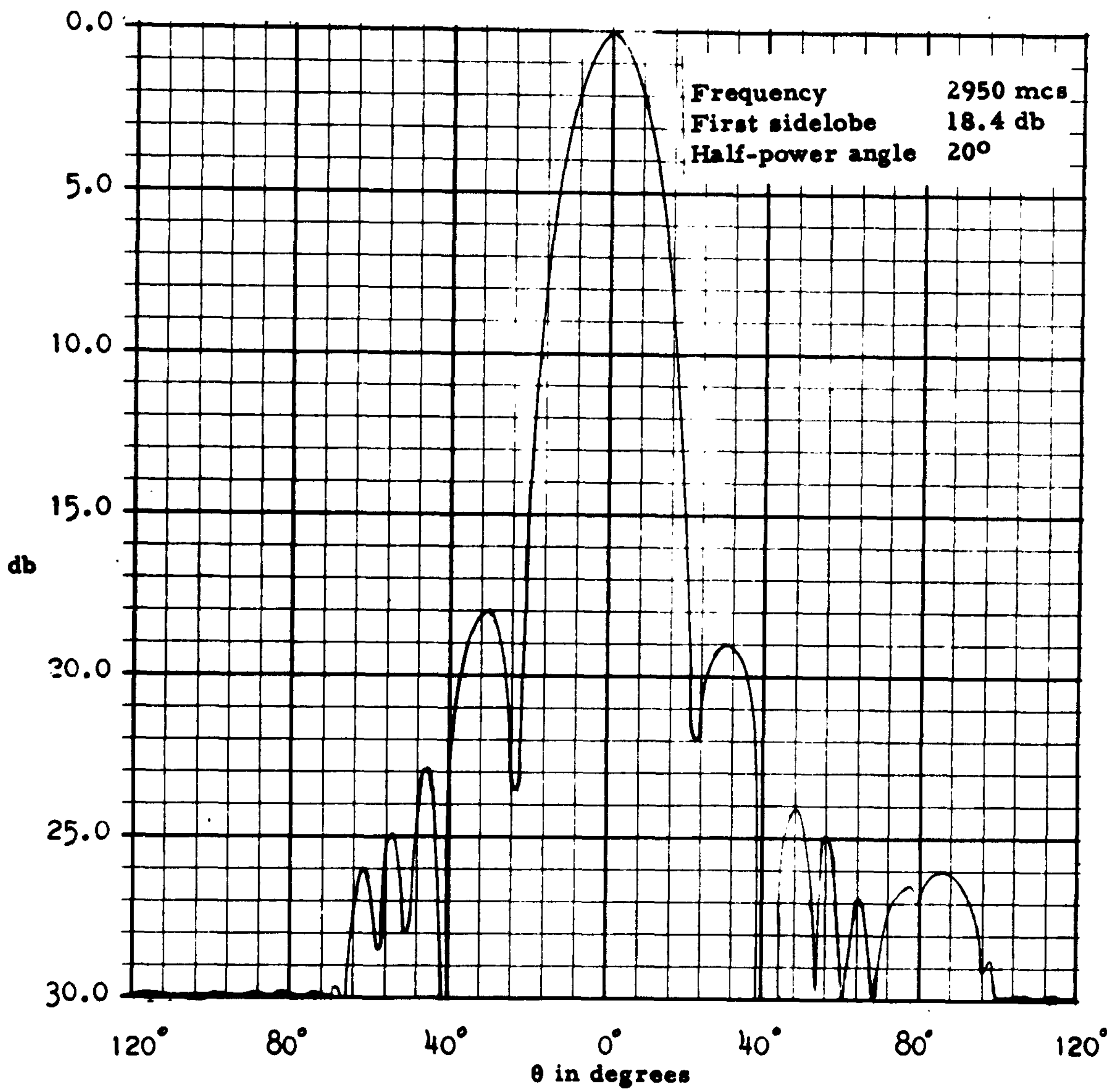

FIGURE 42. Replotted radiation pattern for δ of array given in Figure 27.

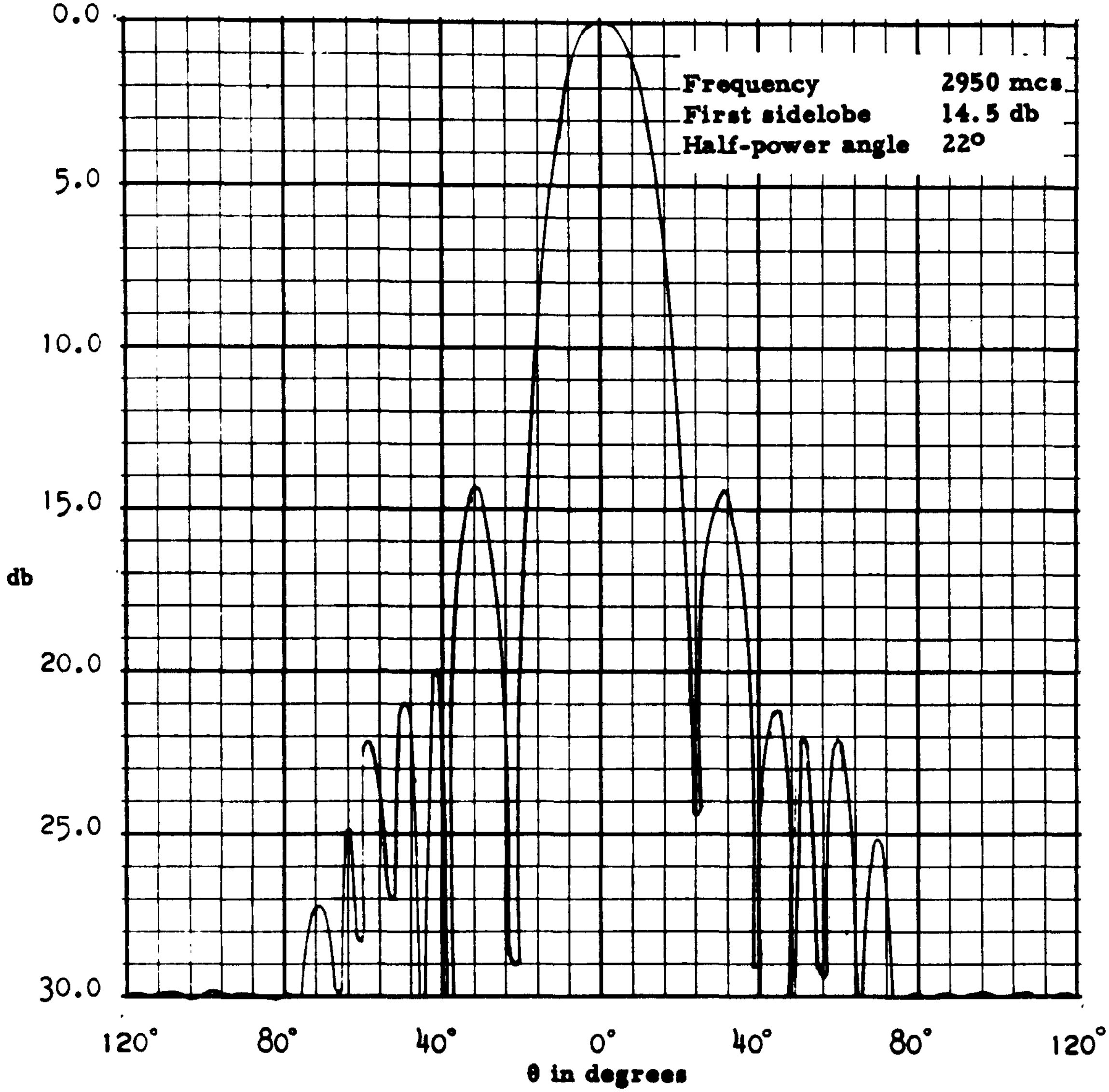

FIGURE 43. **Replotted radiation pattern for δ of array given in Figure 27.**

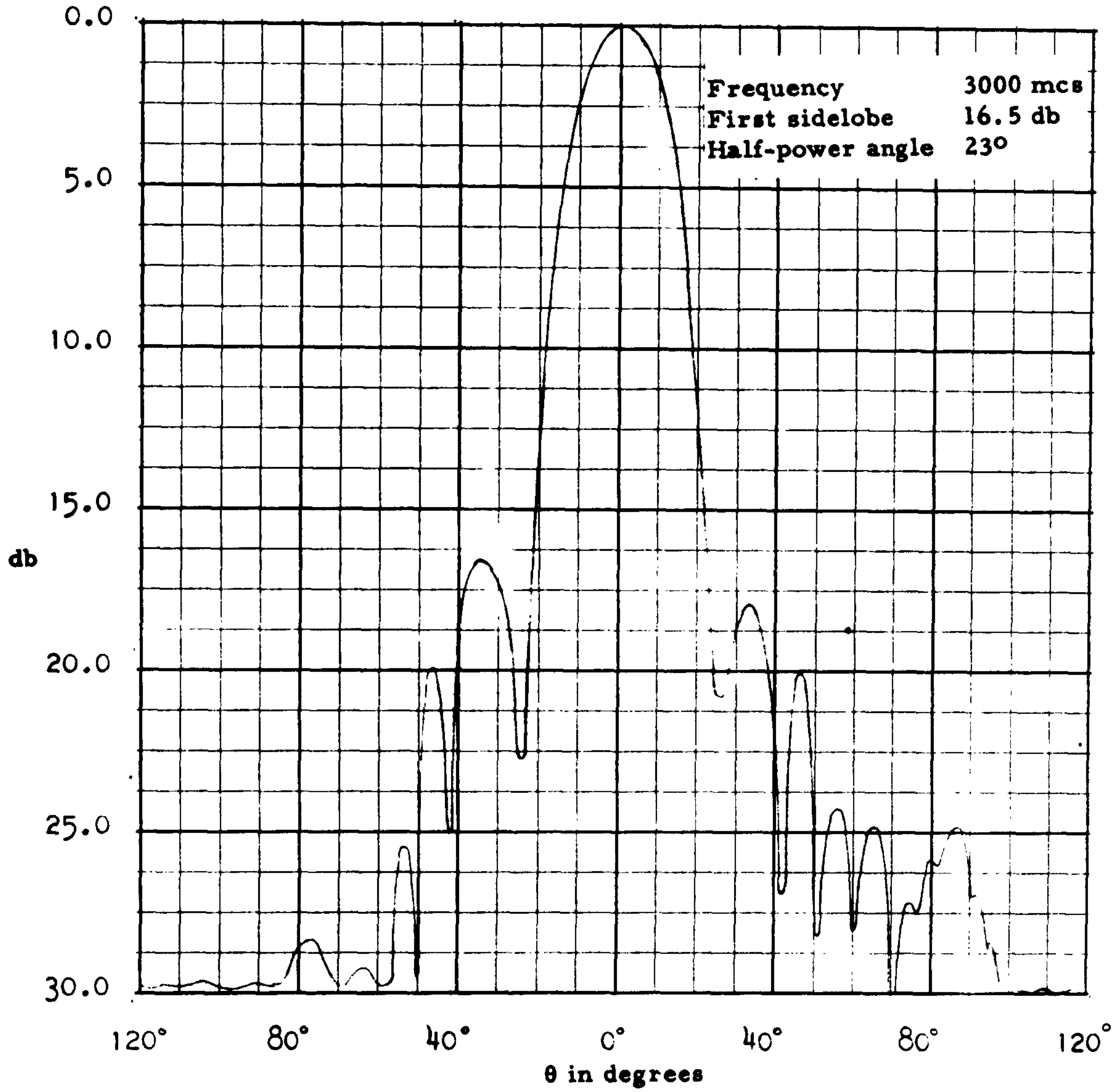

FIGURE 44. **Replotted radiation pattern for δ of array given in Figure 27.**

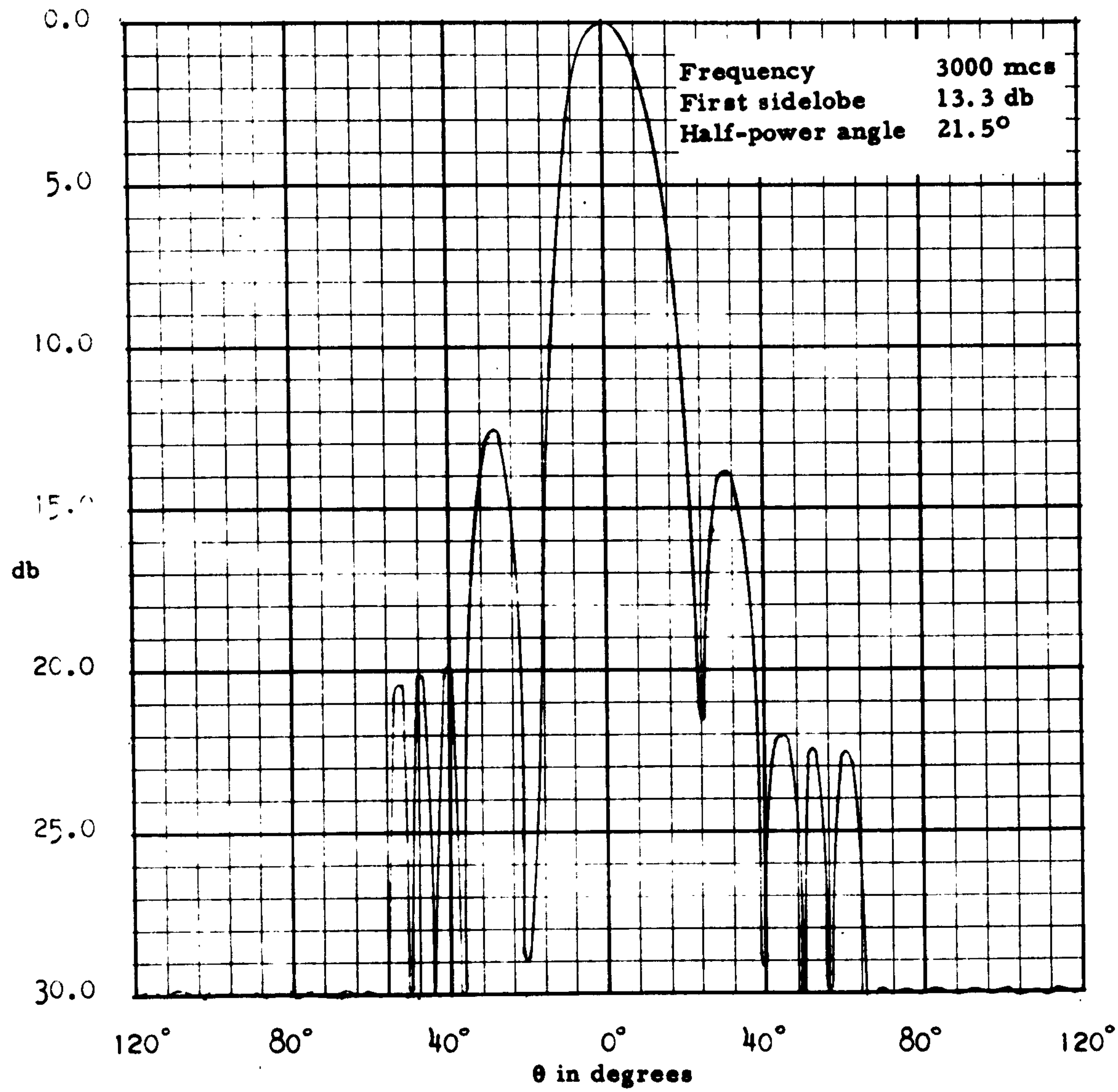

FIGURE 45. **Replotted radiation pattern for δ of array given in Figure 27.**

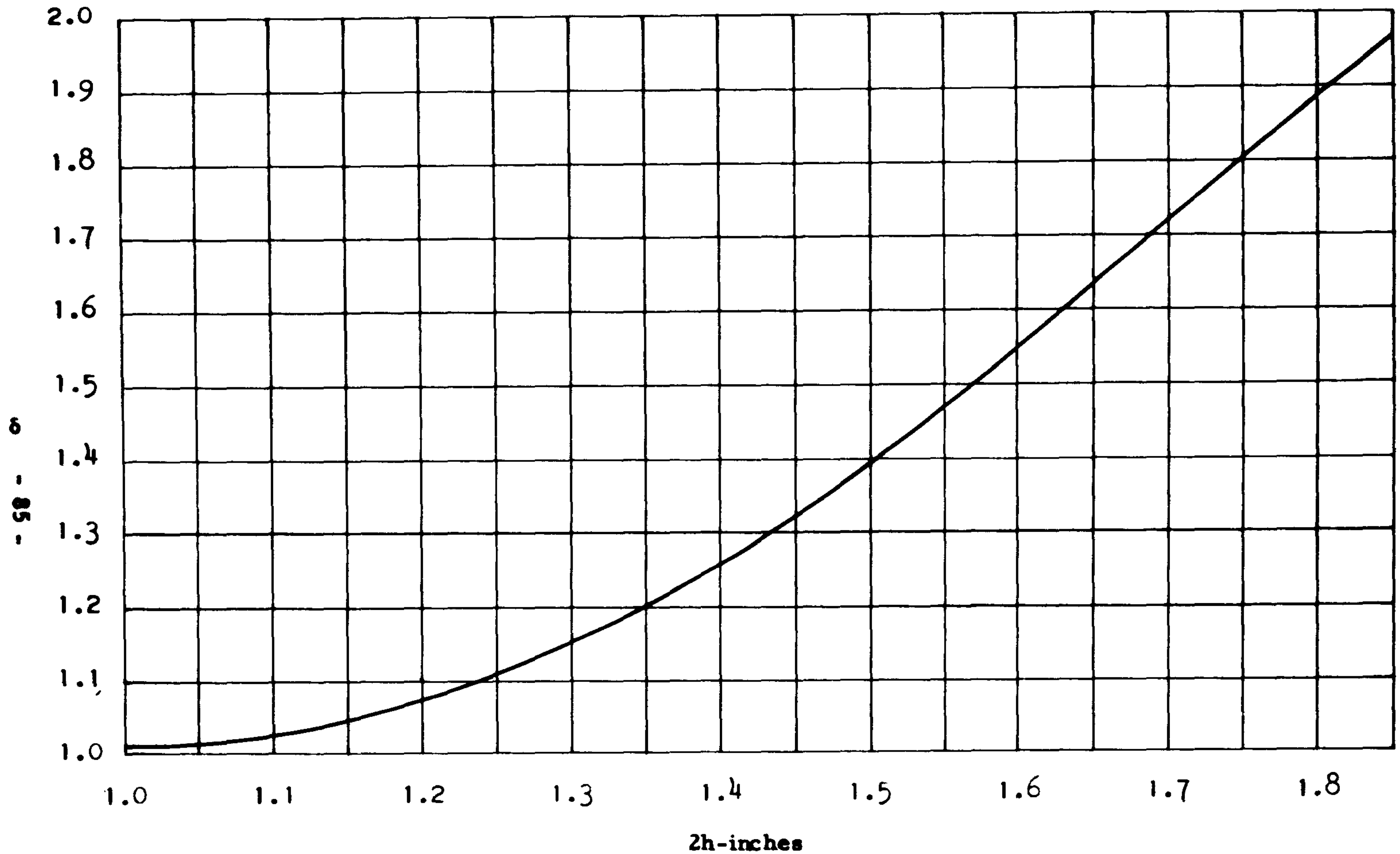

FIGURE 46. δ vs element length in inches for spacing of 0.49 inches center to center.

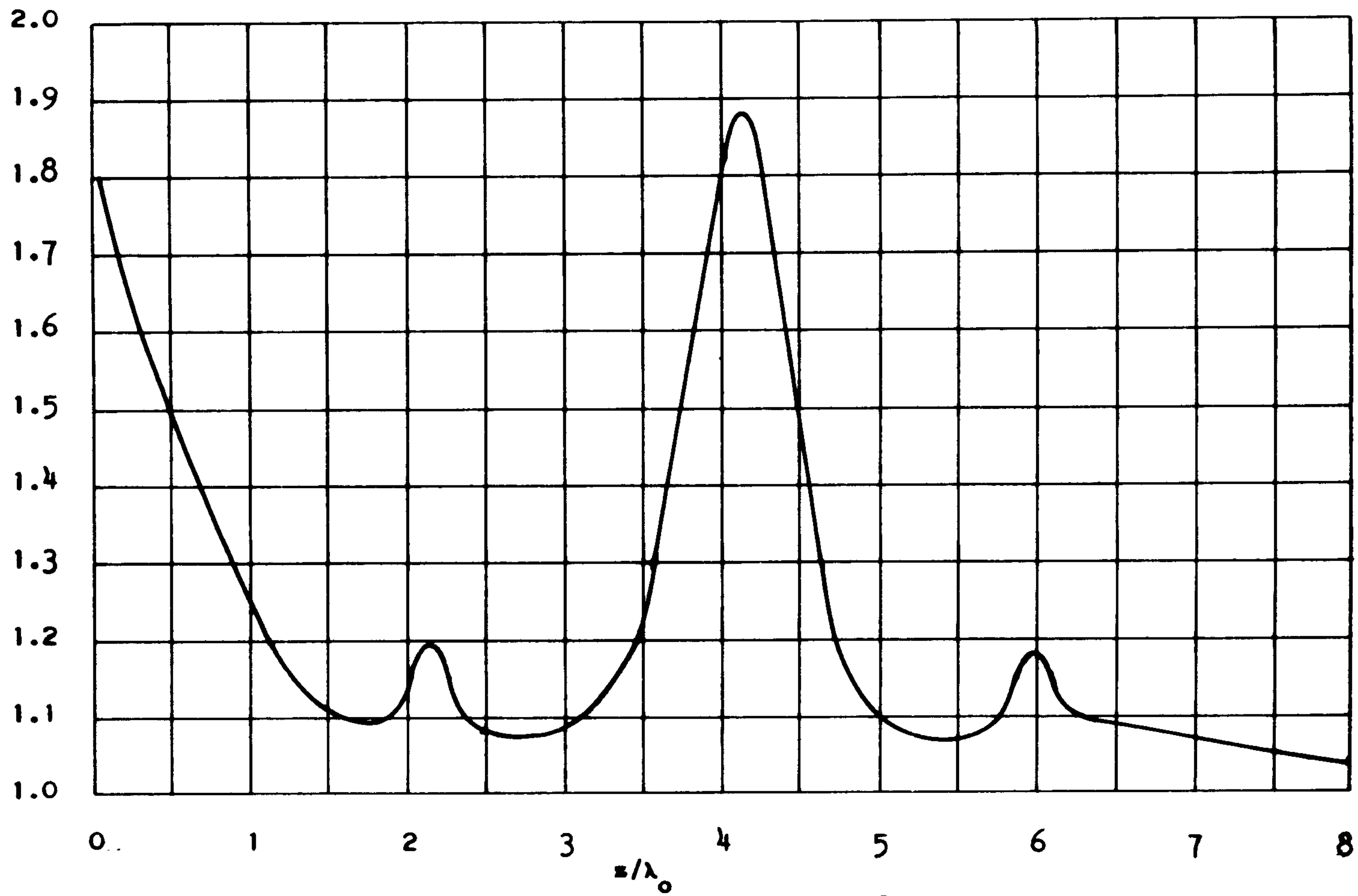

FIGURE 47. Relative wave number vs distance for $8\lambda \csc^2\theta$ array.

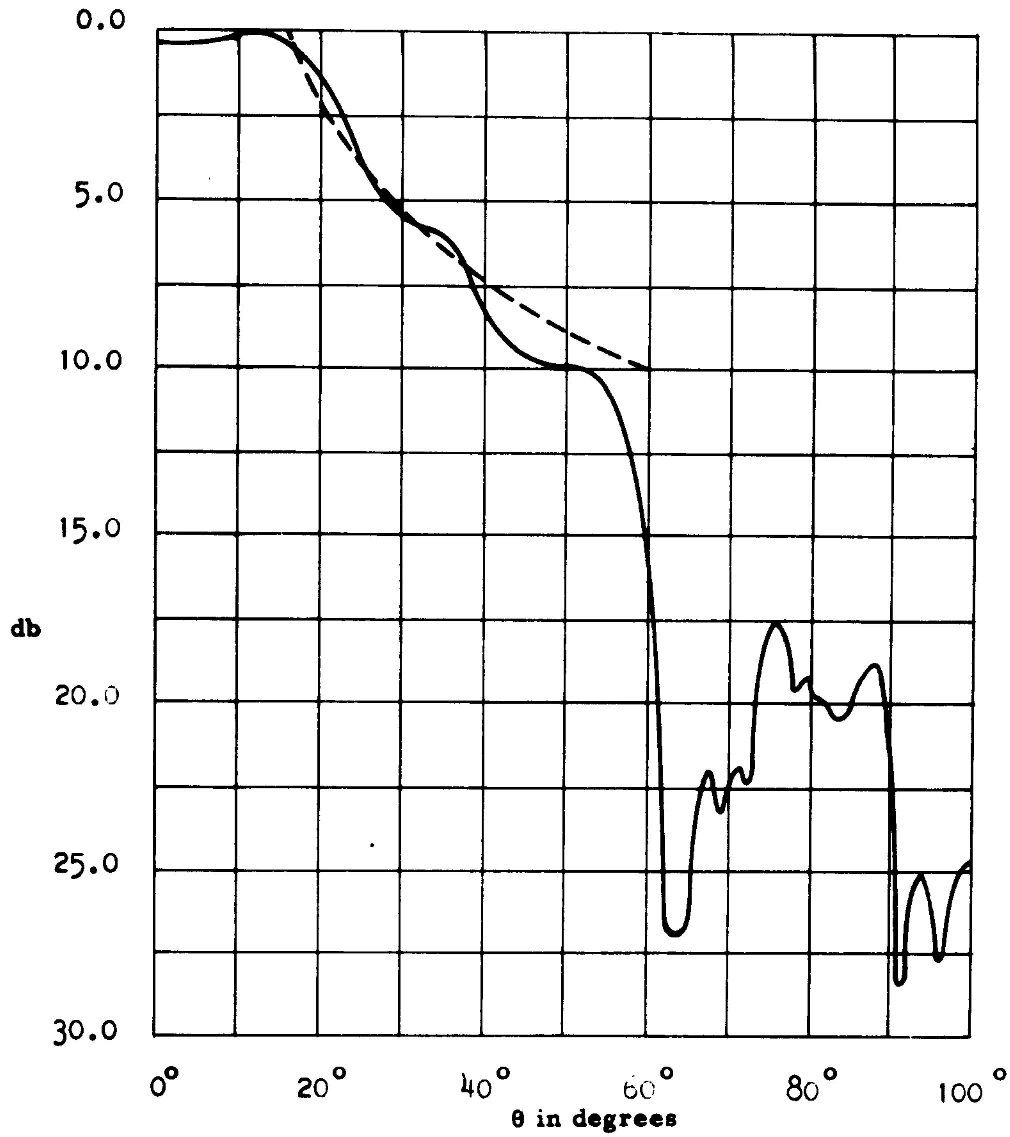

FIGURE 48. **Replotted radiation pattern for array designed according to Figure 47.**

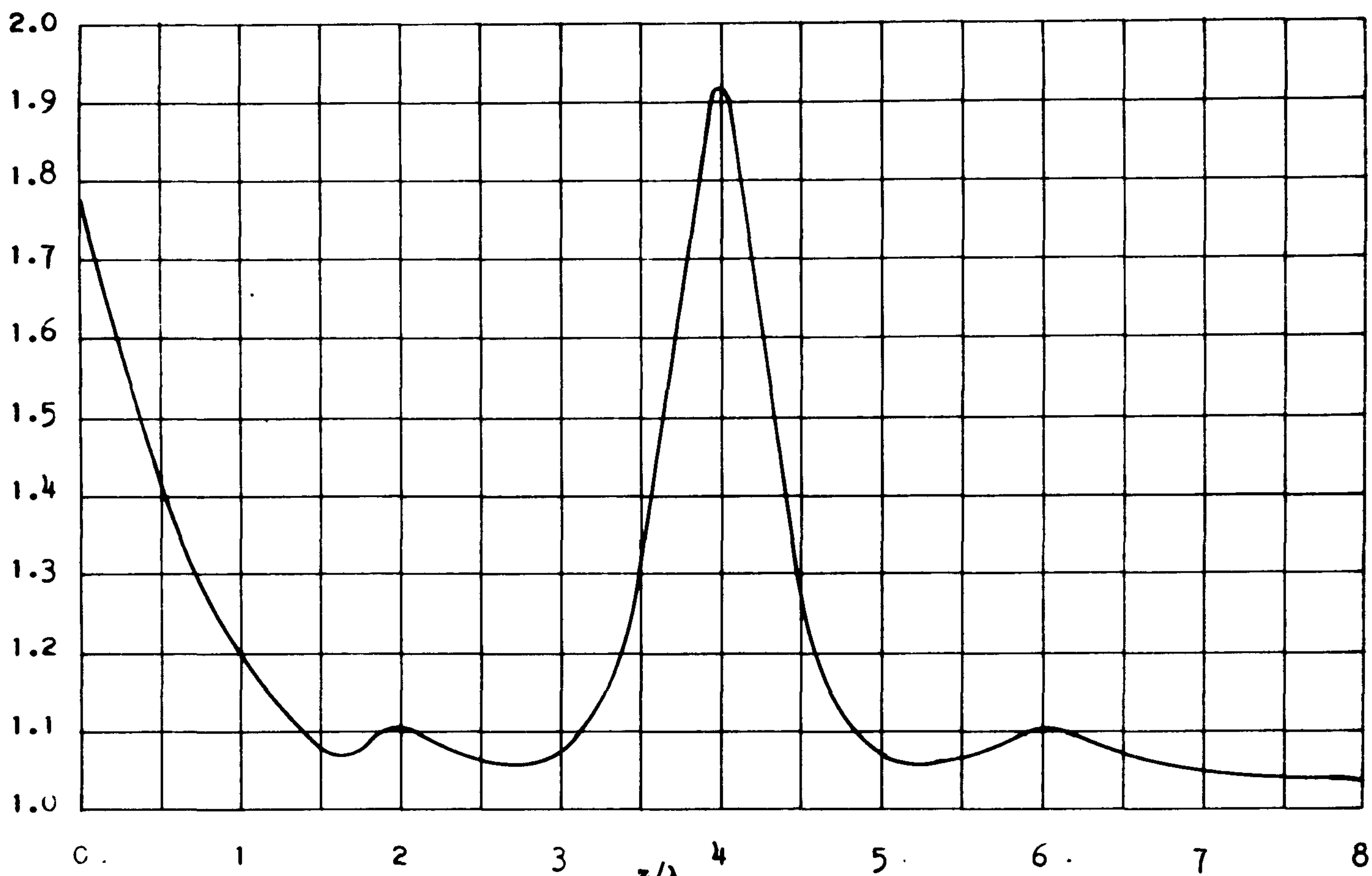

FIGURE 49. Relative wave vs distance for $8\lambda \csc^2\theta \sqrt{\cot\theta}$ array.

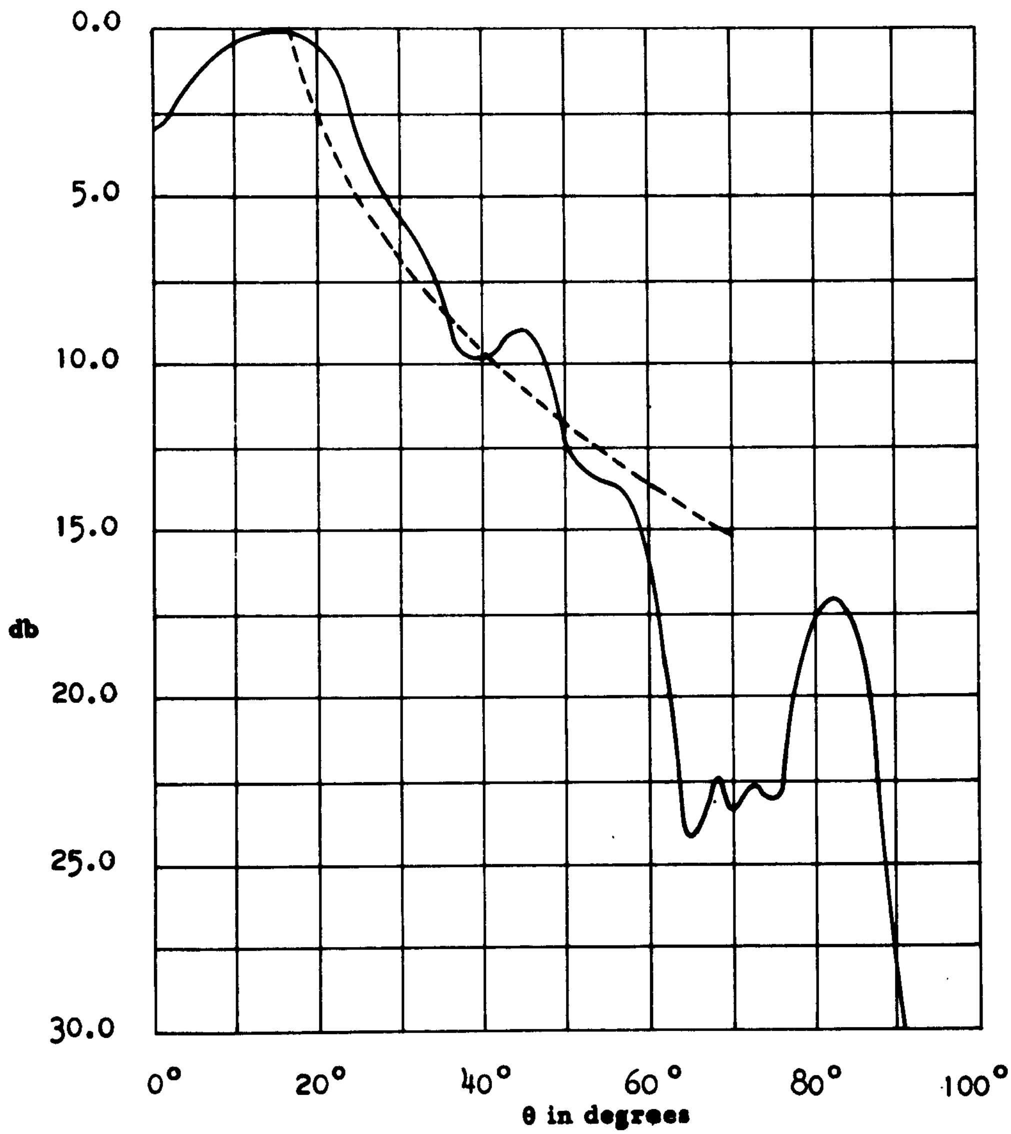

FIGURE 50. **Replotted radiation pattern for array designed according to Figure 49.**

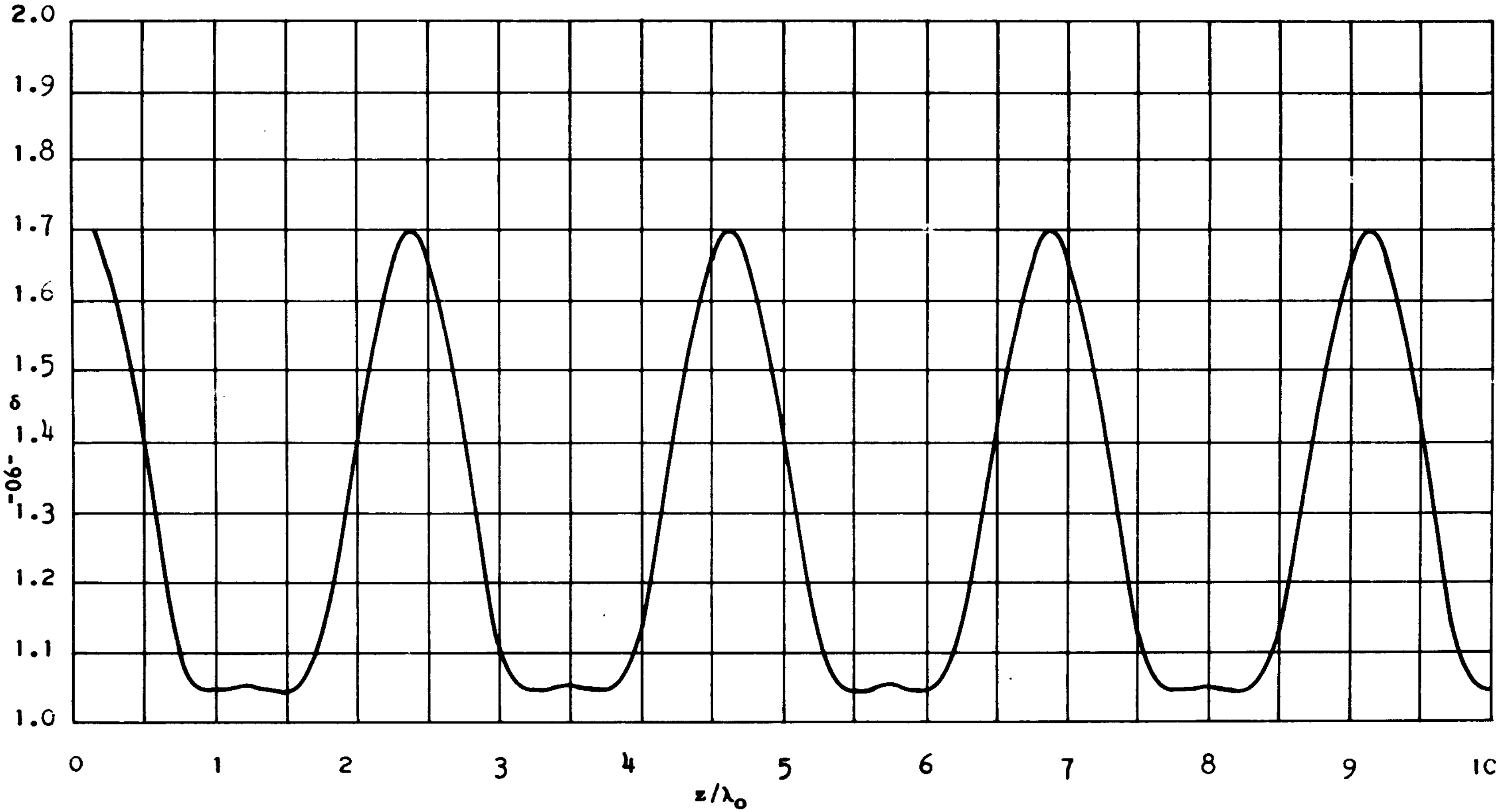

FIGURE 51. Relative wave number vs distance for 10λ array.

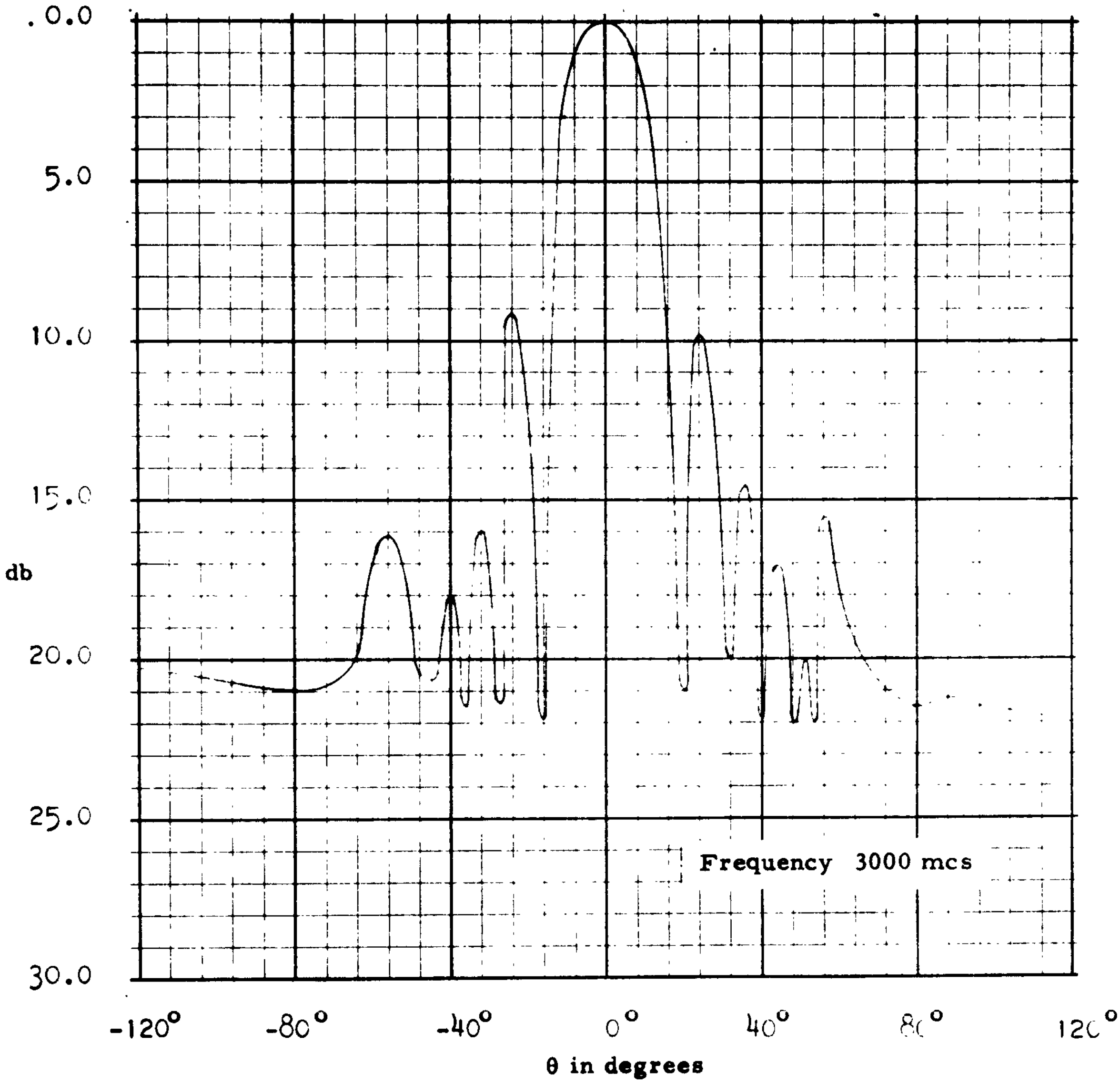

FIGURE 52. Replotted radiation pattern for distribution of Figure 51.

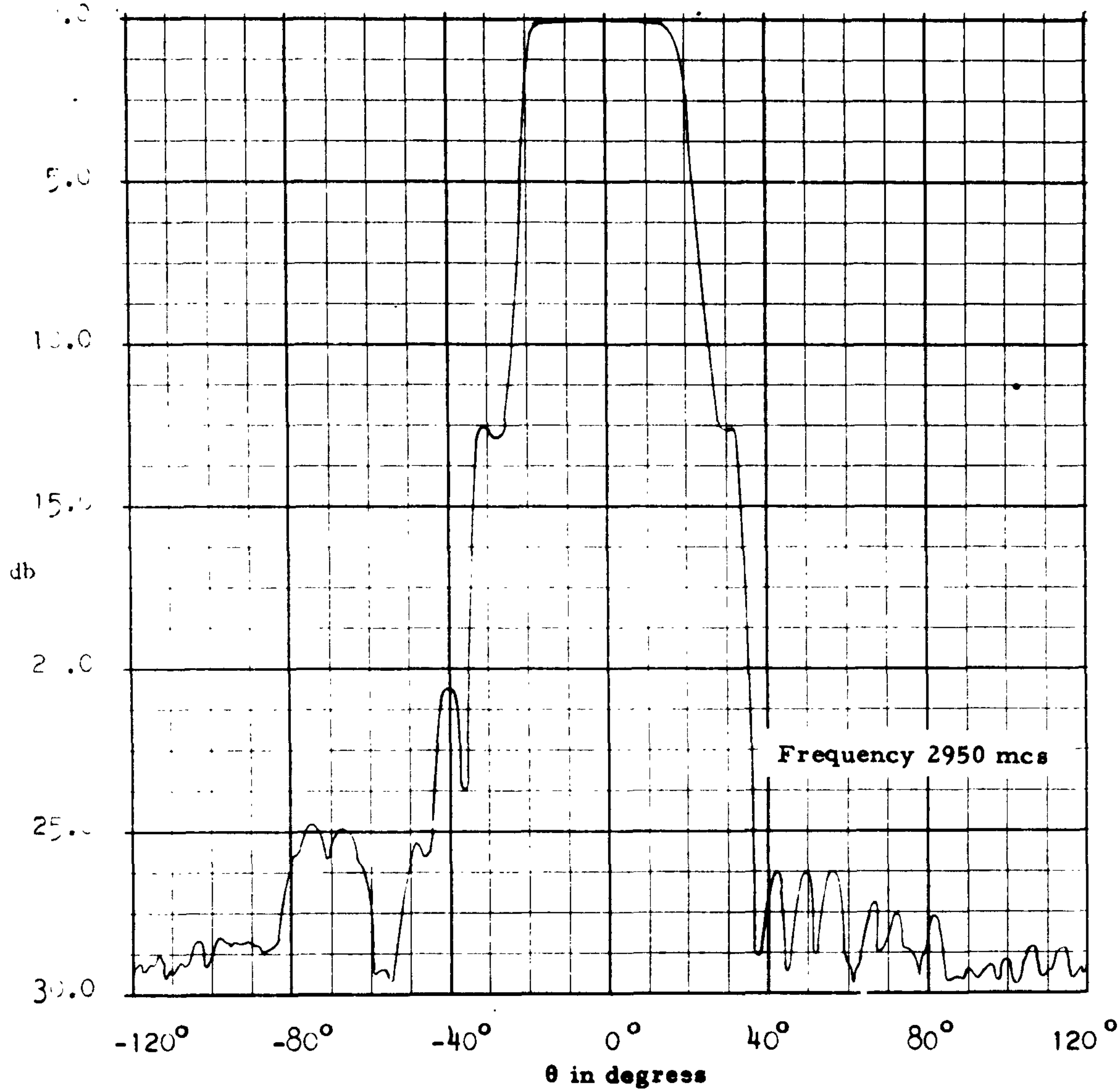

FIGURE 53. Replotted radiation pattern for distribution of Figure 51.

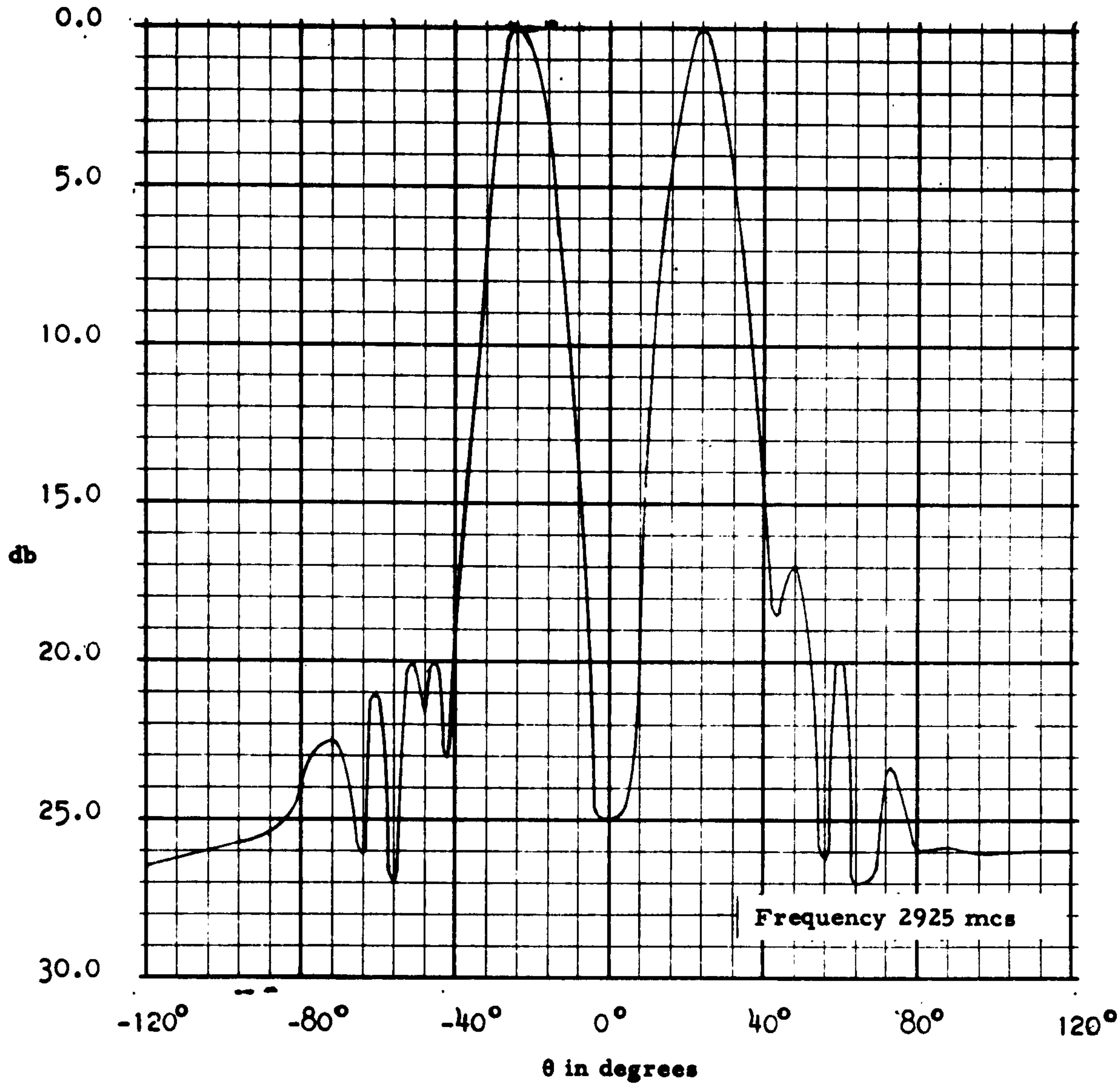

FIGURE 54. Replotted radiation pattern for distribution of Figure 51.

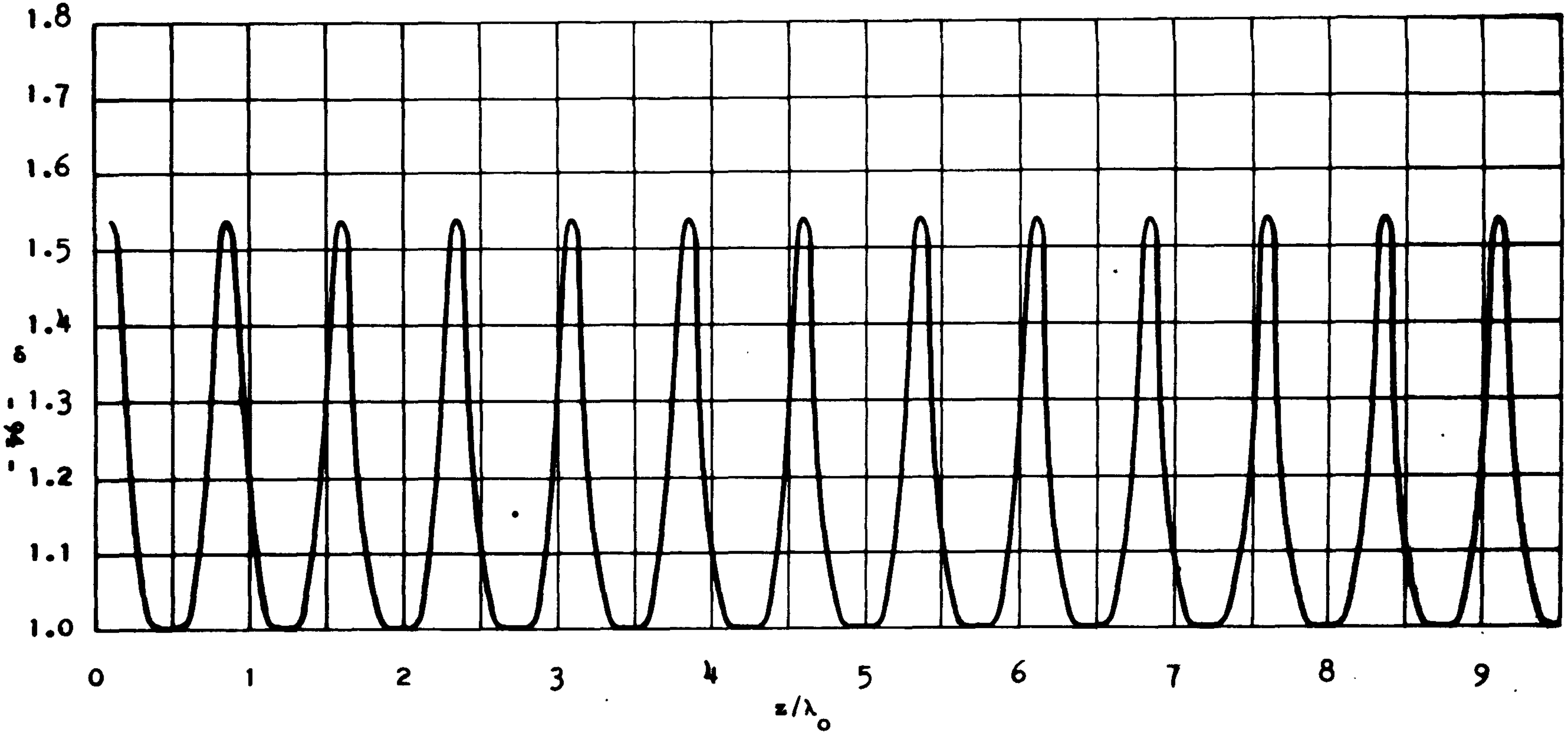

FIGURE 55. Relative wave number vs distance for beam at arbitrary angle array.

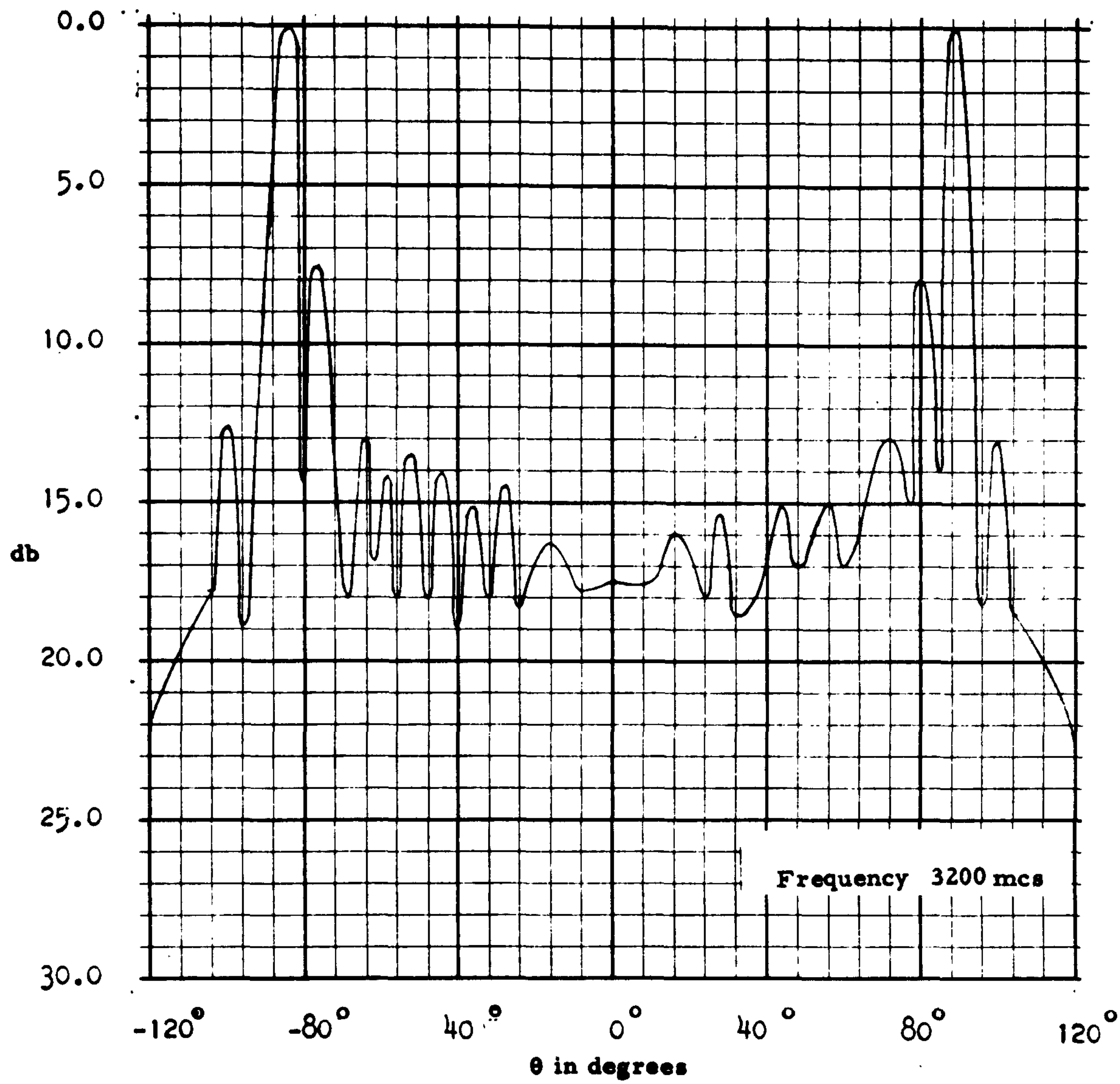

FIGURE 56. **Replotted radiation pattern for distribution of Figure 55.**

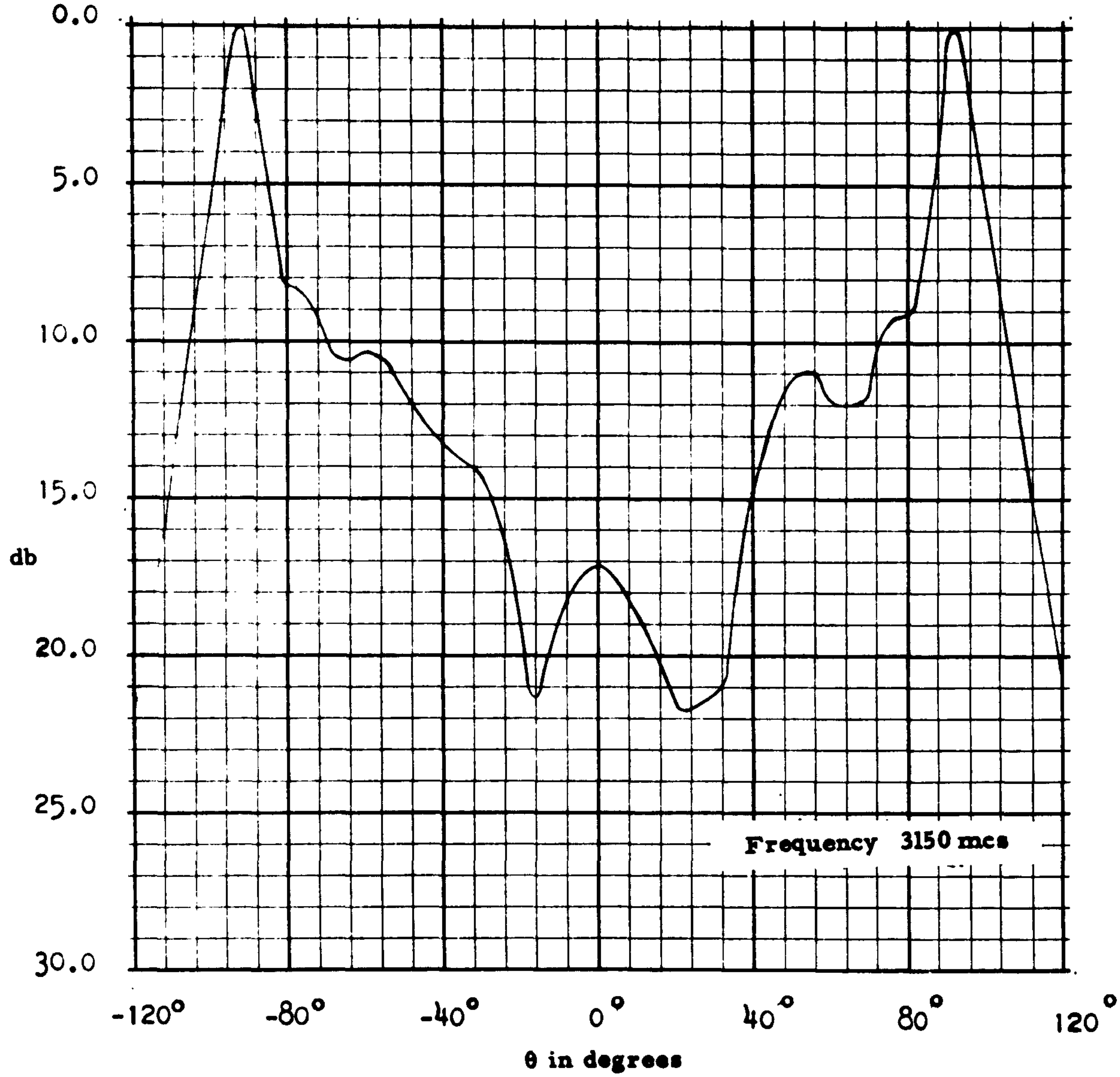

FIGURE 57. **Replotted radiation pattern for distribution of Figure 55.**

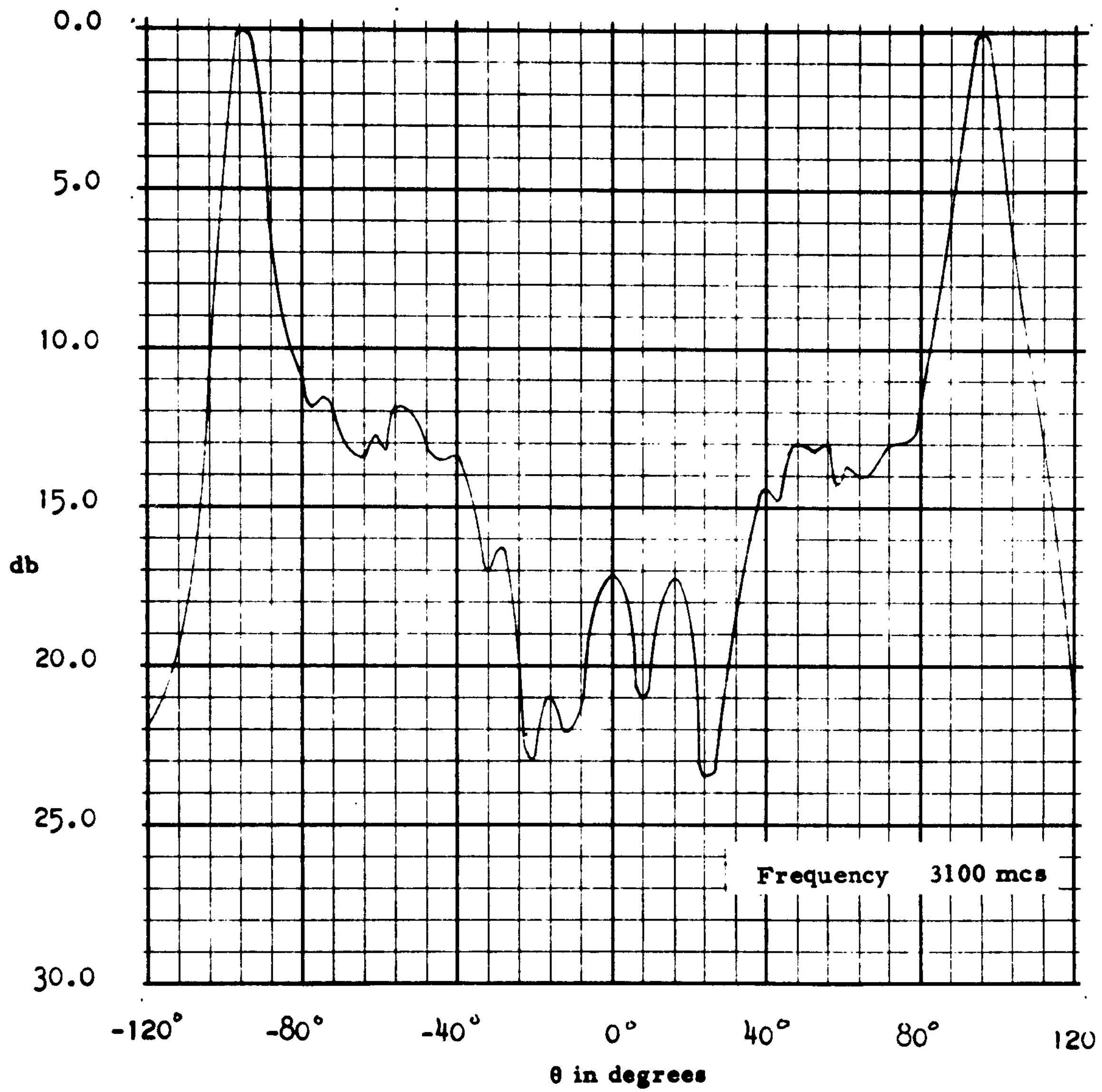

FIGURE 58. Replotted radiation pattern for distribution of Figure 55.

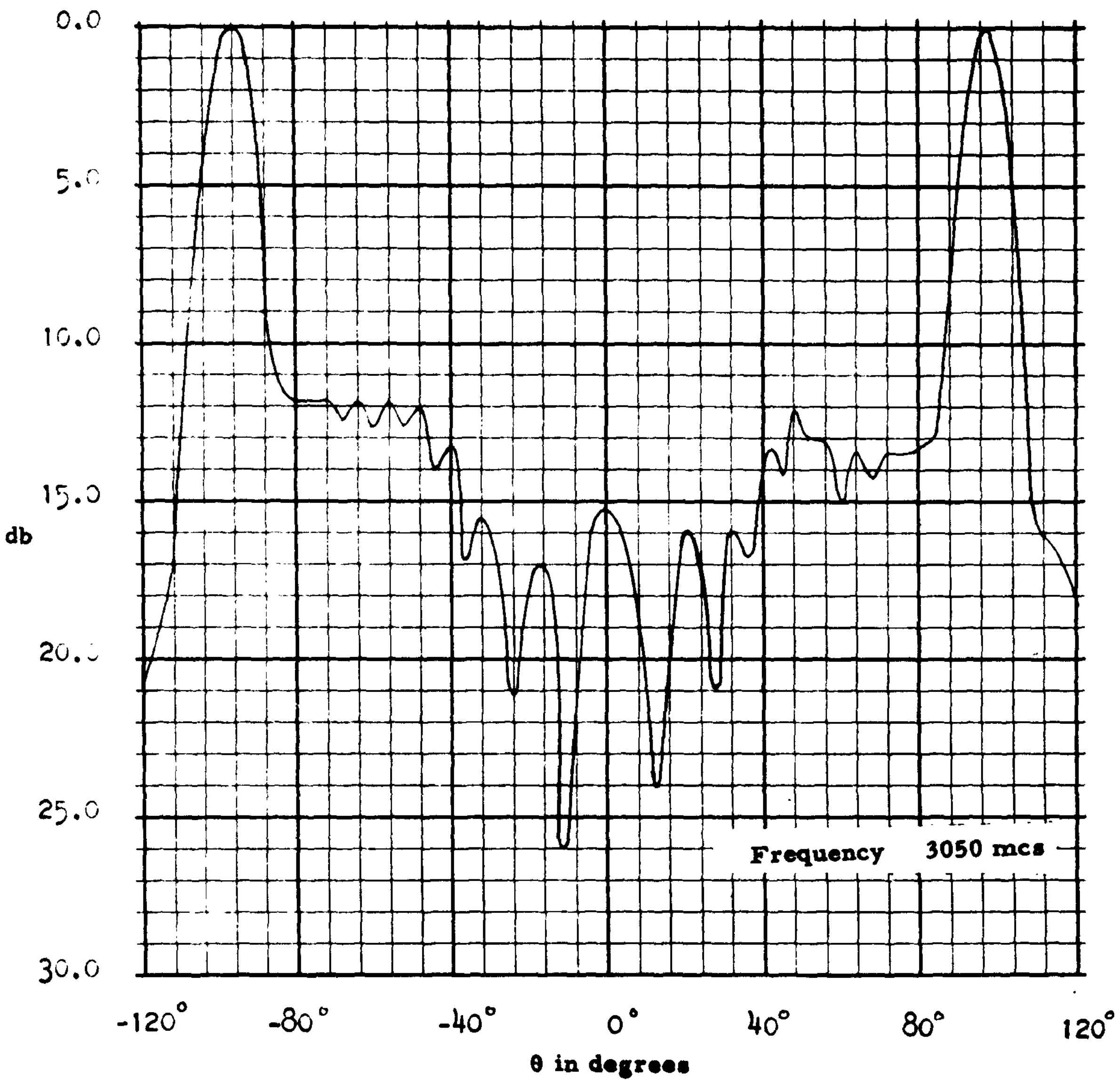

FIGURE 59. Replotted radiation pattern for distribution of Figure 55.

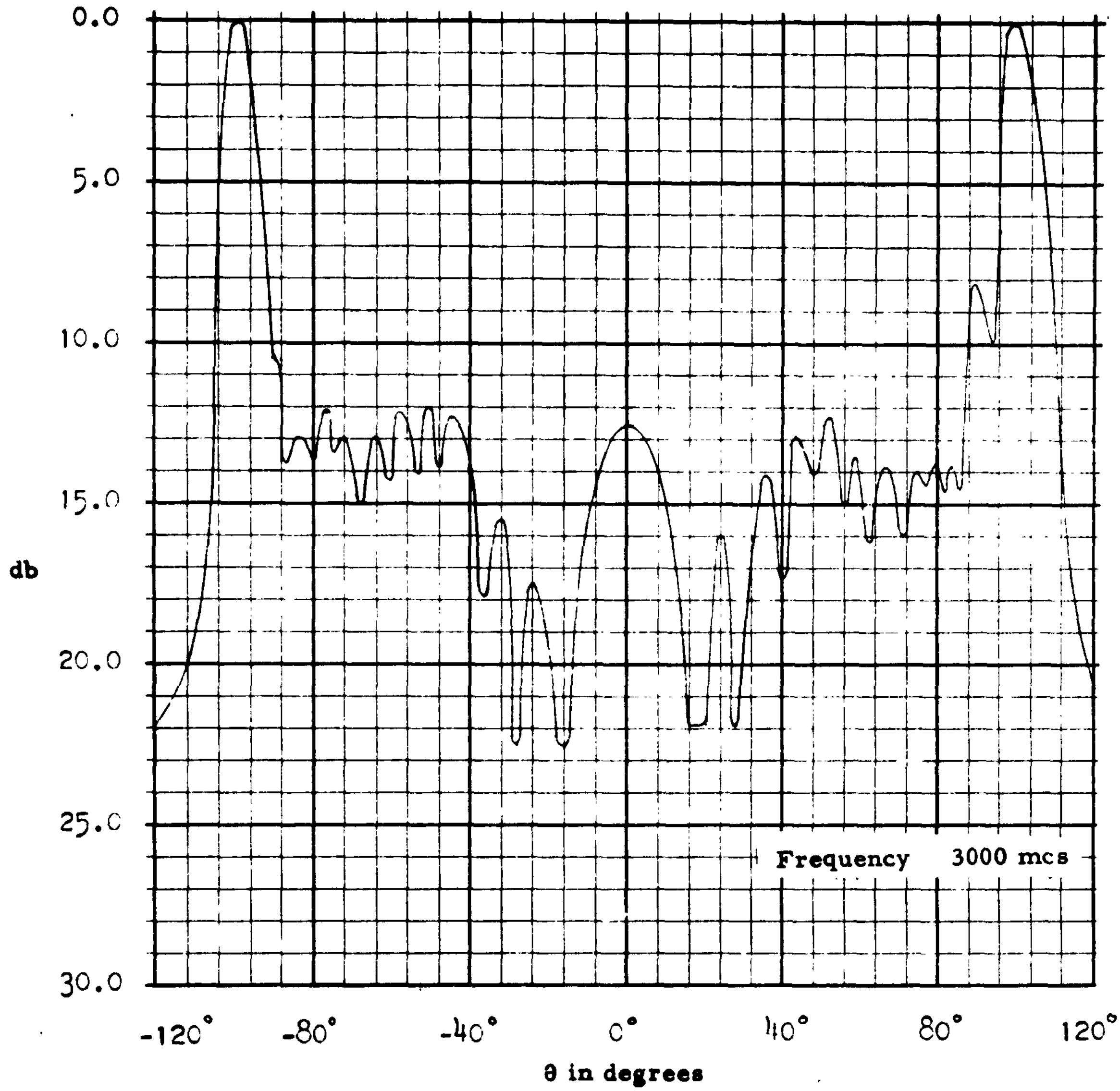

FIGURE 60. Replotted radiation pattern for distribution of Figure 55.

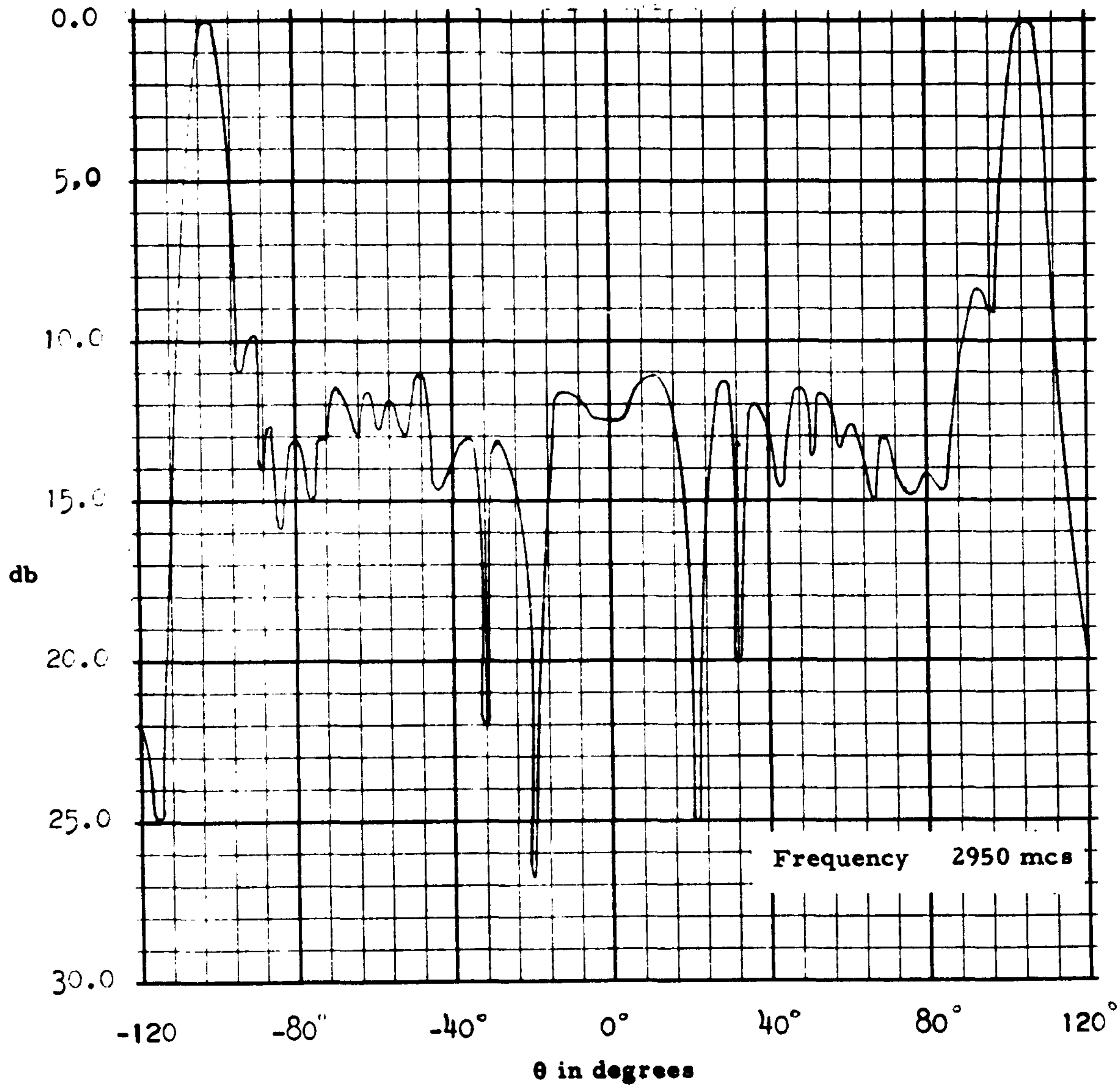

FIGURE 61. Replotted radiation pattern for distribution of Figure 55.

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A. S. Thomas, Inc., 355 Providence Highway, Westwood, Mass.
NEW TECHNIQUES OF PATTERN SHAPING FOR LOW SILHOUETTE ANTENNAS by A. S. Thomas. Final Report December 1962

The infinite modulated reactance sheet is studied with the phase and amplitude contours of the near field presented. It is shown that the infinite reactance sheet is an excellent description of the modulated Yagi. Experimental radiation patterns of low sidelobe endfire arrays are given together with radiation patterns of Yagi arrays giving cosecant type radiations, flat top flared beams, and beams at an arbitrary angle. The beams at an arbitrary angle are obtained from a cosine to the even power modulation of the relative wave number.

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2. Surface Wave Structures
3. Phase Modulation
4. Yagi

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